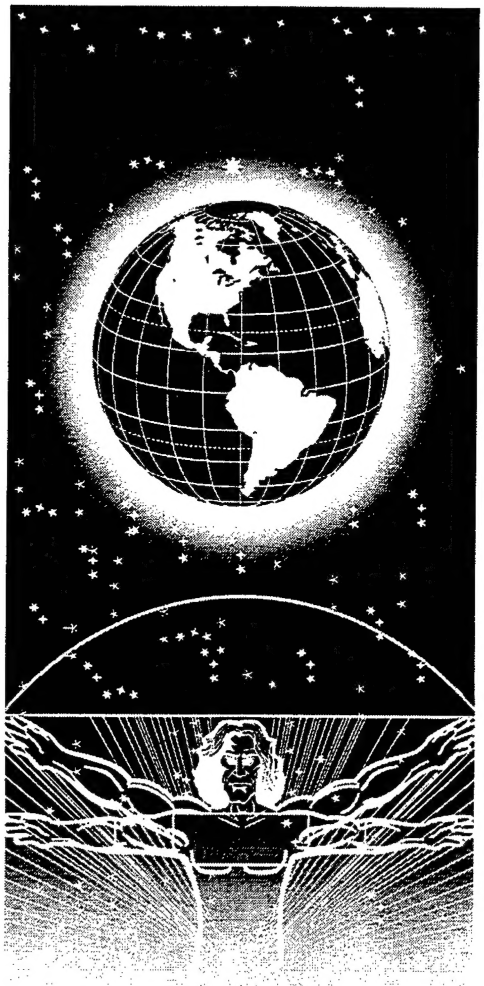
AFRL-HR-BR-TR-2001-0147



UNITED STATES AIR FORCE RESEARCH LABORATORY

PHYSICAL AND OPTICAL EVALUATION OF REFLECTIVE DIELECTRIC LASER EYE PROTECTION (LEP) SPECTACLES

Dennis A. Maier
William R. Brockmeier
Jerry D. Hasten
Peter R. Edsall

TASC
4241 Woodcock Drive, Ste. B100
San Antonio, TX 78228

HUMAN EFFECTIVENESS DIRECTORATE
DIRECTED ENERGY BIOEFFECTS DIVISION
OPTICAL RADIATION BRANCH
8111 18TH Street
Brooks AFB, Texas 78235-5215

September 2001

20011025 091

NOTICES

This report is published in the interest of scientific and technical information exchange and does not constitute approval or disapproval of its ideas or findings.

This report is published as received and has not been edited by the publication staff of the Air Force Research Laboratory.

Using Government drawings, specifications, or other data included in this document for any purpose other than Government-related procurement does not in any way obligate the US Government. The fact that the Government formulated or supplied the drawings, specifications, or other data, does not license the holder or any other person or corporation, or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Leon N. McLin

LEON McLIN, Lt COL, USAF, BSC
Contract Scientist

R Miller

RICHARD MILLER, Ph.D
Chief, Directed Energy Bioeffects Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-01-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2001

2. REPORT TYPE
Interim

3. DATES COVERED *(From - To)*
August 1996 - May 1997

4. TITLE AND SUBTITLE
Physical and Optical Evaluation of Reflective Dielectric Laser Eye Protection (LEP) Spectacles

5a. CONTRACT NUMBER
F41624-97-D-9000

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63231F

6. AUTHORS
Dennis A. Maier
William R. Brockmeier
Jerry D. Hasten
Peter R. Edsall

5d. PROJECT NUMBER
3257

5e. TASK NUMBER
B2

5f. WORK UNIT NUMBER
52

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TASC
4241 Woodcock Drive, Suite B100
San Antonio, TX 78228

8. PERFORMING ORGANIZATION REPORT NUMBER
96-5000-74-2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Human Effectiveness Directorate, Directed Energy Bioeffects Division
Optical Radiation Branch
8111 18th Street
Brooks Air Force Base, TX 78235-5215

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-HE-BR-TR-2001-0147

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
This report was prepared by the Anteon Corporation under Subcontract No. 96-5000-74-2 for TASC, Inc. as part of the WARDOVE Program.

14. ABSTRACT
The physical properties, optical quality, spectral transmittance and laser protection measurements of reflective dielectric laser eye protection (LEP) spectacles supplied by Pilkington Optronics are reported. Research was performed under the Wideband Attenuating Reflective Dielectric Out-of-band Visor Evaluation (WARDOVE) Program whose objective was to define, develop and evaluate reflective dielectric coated out-of-band ALEP visors in the same manner that dye-based absorptive ALEP visors were previously evaluated. Vision performance and human factors evaluations of both reflective dielectric and dye-based LEP spectacles and visors were conducted in the laboratory, in weapon system trainers (WST), and in flight operations. The data presented here document the measured physical performance of the WARDOVE spectacle samples with WD1 and WD2 dielectric coatings prior to any environmental exposure. Discussion of the samples that were evaluated, an overall summary of the physical performance measured, a description of the test methods and instruments, and the detailed data collected are given.

15. SUBJECT TERMS
Laser Eye Protection; Reflective Dielectric; Spectral Transmittance; Ballistic Testing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclass	Unclass	Unclass	UL	55	Lt Col Leon McLin
					19B. TELEPHONE NUMBER *(Include area code)* DSN 240-4816

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION AND BACKGROUND

The physical properties, optical quality, spectral transmittance and laser protection measurements of reflective dielectric laser eye protection (LEP) spectacles supplied by Pilkington Optronics are reported here. With direction and funding supplied by HQ USAF, the **W**ideband **A**ttenuating **R**eflective **D**ielectric **O**ut-of-band **V**isor **E**valuation (WARDOVE) program to evaluate reflective dielectric aircrew laser eye protection (ALEP) was initiated between Armstrong Laboratory (AL) and Wright Laboratory (WL). The WARDOVE program objective was to define, develop and evaluate reflective dielectric coated out-of-band ALEP visors in the same manner that dye-based absorptive ALEP visors were previously evaluated so that an informed, quantitative performance comparison could be made between the reflective dielectric and dye technologies. To accomplish this objective, vision performance and human factors evaluations of both reflective dielectric (supplied by Pilkington Optronics) and dye-based LEP spectacles and visors were conducted in the laboratory, in weapon system trainers (WST), and in flight operations. The physical performance of these LEP devices was evaluated in terms of laser protection, optical quality, spectral transmittance, environmental durability, and ballistic impact.

Anteon Corporation, in support of WL/MLPJ, contracted with TASC, Inc., to perform the physical properties, optical quality, spectral transmittance and laser transmittance measurements of spectacle and visor reflective dielectric LEP provided under the WARDOVE program. Because of delays in the delivery of the ALEP visors from Pilkington, the contract was modified to include measurements on spectacle samples only.

Pilkington Optronics, St. Asaph, Wales, was contracted to supply dielectric coated polycarbonate LEP spectacles and visors for evaluation in the WARDOVE program. Two different dielectric coatings were supplied. The first coating, the existing coating developed by Pilkington for far-red and near-infrared laser protection, was designated as WD1. The second coating, a newly designed and produced coating that had a wider transmittance band and did not provide laser protection in the far-red portion of the spectrum, was designated as WD2. Because of the developmental nature of dielectric LEP, the performance of the dielectric coated LEP spectacles and visors to be supplied by Pilkington was specified in terms of performance goals rather than requirements.

The data presented here document the measured physical performance of the WARDOVE spectacle samples with WD1 and WD2 dielectric coatings prior to any environmental exposure. This report discusses the samples that were evaluated, provides an overall summary of the physical performance measured, describes the test methods and instruments, and displays the detailed data collected.

WARDOVE SPECTACLE SAMPLE DESCRIPTION

Pilkington delivered forty pair of reflective dielectric LEP spectacles: twenty with the WD1 coating and twenty with the WD2 coating. Each pair of spectacles contained two lenses. Each lens consisted of a six diopter base curve and a plano-polycarbonate cap approximately 1.5 mm thick. The reflective dielectric coating was applied to the concave side of this cap. A polycarbonate substrate of approximately 1.5mm thickness was optically cemented (laminated) to the coated side of the substrate in order to provide environmental protection to the dielectric coating. Five pair of spectacles (ten lenses) with each of the two different dielectric coatings were supplied to the University of Dayton Research Institute (UDRI) for environmental testing. Ten spectacle samples (twenty lenses) of each coating type (40 lenses total) were evaluated by TASC, Inc., for physical properties, optical quality and spectral transmittance. These ten pair of spectacles were used in laboratory, flight simulator, ground and flight aircraft vision testing. Great care was taken to maintain the integrity and quality of the spectacles intended for vision testing. Five pair (of the ten pair) of spectacles of each coating (ten lenses with each coating) were measured for laser optical density at 0, 30 and 50 degrees from normal incidence. Destructive physical properties testing, such as scratch, abrasion, and impact resistance, was performed on a limited number of samples that were not needed for vision or flight evaluation.

In an evaluation program for developmental LEP such as WARDOVE, the unique designation of each lens and each pair of spectacles is critical for correlating vision performance and pilot acceptance with the physical and optical performance. Each pair of spectacles with the two different coatings was numbered 1 to 20 by Pilkington Optronics prior to delivery. TASC further designated the samples for data traceability. The designation system for the WARDOVE spectacle samples is shown in Figure 1. An eight-character designator is assigned to each data file related to the WARDOVE measurements. The designation system was selected to uniquely designate each measurement on each sample within the eight-character file designation constraint of DOS-based computer files. The designation for specific locations on each lens of the WARDOVE spectacles is shown in Figure 2.

Q 01 S 1 L P 1

Angle of incidence (0 = 0deg, 1 = 10deg, 2 = 20deg)

Polarization (p = parallel, s = perpendicular, u = unpolarized, d = unknown)

Position on lens (see Figure 2)

Coating or FV number (1 = WD1, 2 = WD2, 9 = FV9)

Sample type (S = spectacle, V = visor)

Sample number (Pilkington or Glendale assigned number)

Manufacturer and Program
(Q = Pilkington WARDOVE; Z = Willson Eyewear WARDOVE)

Figure 1: WARDOVE Sample and File Designation System.

To illustrate the designation of a measurement: The designator Q02S1L indicates that the measurement was on a WARDOVE sample manufactured by Pilkington (Q), sample number 2 (02), a spectacle(S) sample, with coating WD1(1) on the left lens-center location (L). The lack of the last two designation fields indicates that they do not apply to this measurement.

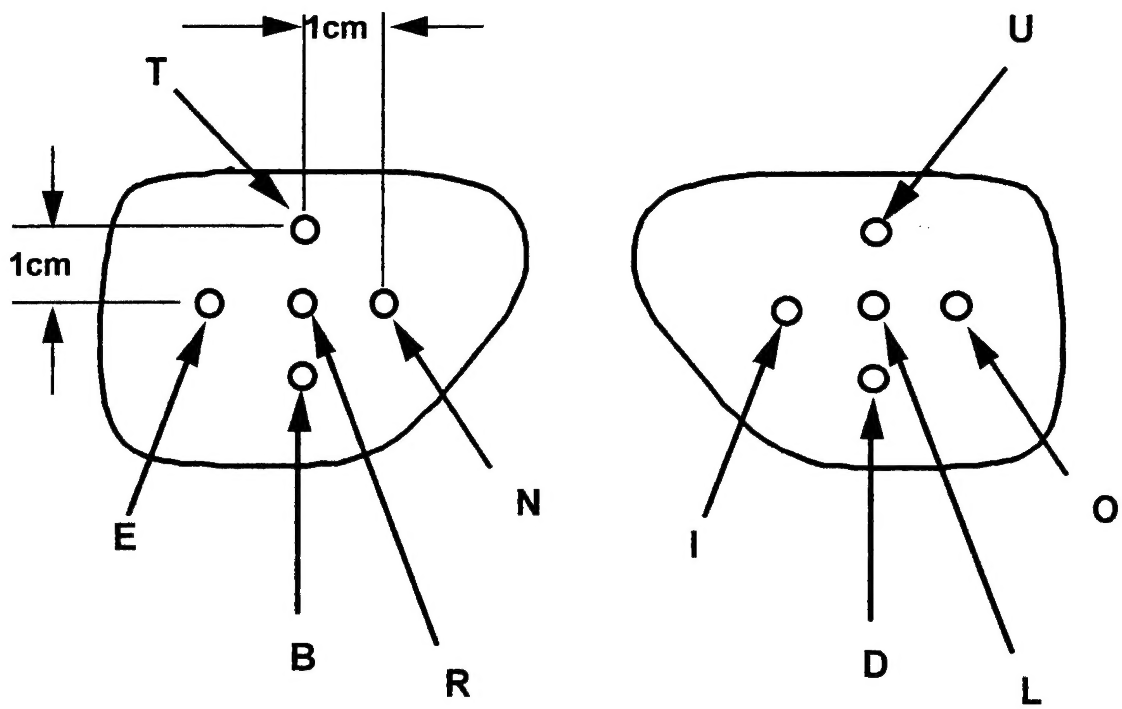


Figure 2: WARDOVE Spectacle Location Designation (view from outside of spectacles looking toward wearer).

SUMMARY OF PERFORMANCE MEASUREMENTS

All ten pair of WARDOVE spectacles, each with the WD1 and WD2 coatings (20 lenses with each coating, 40 lenses total), that TASC evaluated were found, in general, to be good to excellent in terms of cosmetic quality, optical quality (except for prismatic deviation), spectral transmittance, and hardcoating durability. The prismatic deviation exceeded the recommended amount in several of the lenses and spectacles. The spectral transmittance and laser protection of both WD1 and WD2 spectacles closely matched the design goals. The five pair of spectacles with WD1 and WD2 coatings (10 lenses with each coating, 20 lenses total) that were measured for laser optical density exceeded the required 4.0 OD level of laser protection at all angles up to 50 degrees from normal. The specific optical quality measurements performed included refractive power, prismatic deviation, haze, and distortion. The spectral transmittance of all samples was measured from 200 to 1200 nanometers (nm) for angles of incidence of 0, 30, and 50 degrees. The photopic and scotopic luminous transmittance, the CIE chromaticity coordinates, the ultraviolet transmittance, and the optical density at specific wavelengths were all computed from the spectral transmittance data. The laser optical density was measured for five of the samples (10 lenses of each coating type) at 0, 30 and 50 degrees angles of incidence using a laser densitometer. The scratch resistance, abrasion resistance, and coating adhesion were measured on one lens of each type of coating. A ball drop impact test was performed on one lens of each type of coating. The physical thickness of the 40 lenses was measured at 5 locations. In this summary, the maximum, minimum and average values of the measured and computed performance parameters for the ten pair of WARDOVE spectacles with each of the two different coatings are given. The performance values specified in ANSI and Military Standards are given for comparison. A complete discussion of the measurements and the detailed values of the performance parameters for each lens and each pair of spectacles is included in later sections. Complete spectral transmittance and spectral optical density curves from 200 to 1200 nm for each lens at three angles of incidence are provided as Appendix A.

Physical Properties

Cosmetic Quality All WD1 and WD2 spectacle lenses evidenced small inclusions and specks, apparently in the lamination layer. In most instances these cosmetic defects were only visible under intense light and were not visible as worn.

Thickness (mm) Measured at five locations on 20 lenses of each coating type.

	Max.	Min.	Average	Maximum Variation
WD1	3.24	3.02	3.14	.09
WD2	3.57	3.00	3.20	.21

Hard Coating Durability Hard coating adhesion, scratch resistance and abrasion resistance of the WARDOVE lenses tested were all very good.

Impact Resistance The impact resistance of the WARDOVE lenses subjected to the ball drop test was good. The dielectric coating did, however, crack at the location of the impact.

Optical Quality

Prismatic Deviation (prism diopters)

	Max.	Min.	Average	MIL-V-43511C	ANSI Z87.1 89
Up/Down				< |.18 |	< |.06 |
WD1	.05	-.23	-.08		
WD2	.15	-.36	-.06		
In/Out				not specified	< |.13 |
WD1	.31	-.03	.16		
WD2	.48	-.08	.18		
Horizontal Sum				< |.50 |	< |.50 |
WD1	.45	.06	--		
WD2	.47	.27	--		
Horizontal Difference				< |.18 |	< |.13 |
WD1	.28	-.14	--		
WD2	.56	-.49	--		
Vertical Difference				< |.18 |	< |.13|
WD1	.16	-.10	--		
WD2	.12	-.16	--		

Refractive Power (diopters)

	Max.	Min.	Average	MIL-V-43511C	ANSI Z87.1 89
Vertical				< |.125 |	< |.06 |
WD1	.04	-.09	.01		
WD2	.07	.00	.03		
Horizontal				< |.125 |	< |.06 |
WD1	.22	-.17	-.02		
WD2	.06	-.01	.03		
Astigmatism				not specified	< |.06 |
WD1	.16	-.22	.01		
WD2	.04	-.04	.00		

Haze (%) Measured on BKY Gardner XL -211 Hazemeter (adjusted for residual). The performance goal was < 1%.

	Max.	Min.	Average	MIL-V-43511C	ANSI Z87.1 89
Haze				< 2%	< 3%
WD1	2.04	1.29	1.67		
WD2	1.74	1.25	1.46		

Distortion All WD1 and WD2 lenses evidenced little, if any, distortion. All lenses were rated either a P1 or P2 when compared to Figure 1 on Page 17 of MIL-V-43511C. These ratings are the two best ratings.

Transmittance

Spectral Transmittance The spectral transmittance curves of the WARDOVE spectacles were very near the ideal curves that were specified. The expected blue shift of the spectral transmittance curves with increasing angles of incidence was noted. The spectral transmittance curves for typical WD1 and WD2 coatings are given in Figure 3. Appendix A contains all of the transmittance and optical density curves.

Photopic Luminous Transmittance (%) at 0° angle of incidence.

	Max.	Min.	Average
WD1	81.4	71.8	75.2
WD2	84.6	81.3	82.6

Scotopic Luminous Transmittance (%) at 0° angle of incidence.

	Max.	Min.	Average
WD1	77.9	69.9	72.9
WD2	78.9	76.0	77.1

Laser Optical Density (OD) Five pair of spectacles of each coating (ten lenses) at 0, 30, 50° relative to normal.

	λ=694.3		λ=1064	
0° ANGLE	Max.	Min.	Max.	Min.
WD1	5.46	4.41	6.15	5.72
WD2	---	---	6.80	4.18
30° ANGLE	λ=694.3		λ=1064	
	Max.	Min.	Max.	Min.
WD1	5.65	4.83	6.32	5.93
WD2	---	---	7.07	4.23
50° ANGLE	λ=694.3		λ=1064	
	Max.	Min.	Max.	Min.
WD1	5.60	4.83	6.24	5.54
WD2	---	---	6.36	4.80

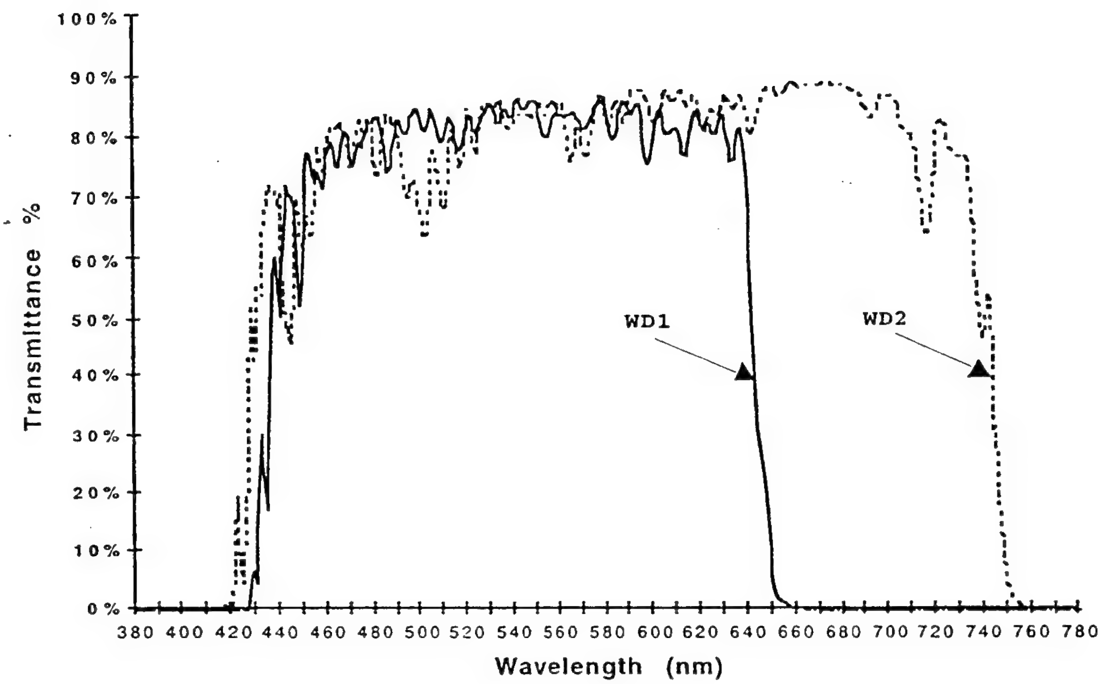


Figure 3. Spectral Transmittance Curves of WD1 and WD2 Reflective Dielectric LEP, 0 degrees.

DESCRIPTION OF PERFORMANCE PARAMETERS, TEST METHODS, INSTRUMENTS AND RESULTS

This section contains discussions of the performance parameters and the methods and instruments used to measure the performance parameters of the WARDOVE LEP spectacle lenses. The physical properties, optical quality, spectral transmittance and the laser optical density measurements that were made are discussed in the sub-sections below. The significance of the performance parameters in terms of protection afforded, human performance or aircrew acceptance, and/or survivability of the LEP in an operational environment is discussed. The methods and instruments used to make the measurements are described and the detailed measured data is discussed and presented in tables.

Physical Properties

The physical properties that were measured included: (1) the thickness at five different locations on each lens; (2) the cosmetic quality of the lenses; (3) stresses evident in crossed polarizers; (4) hardcoating adhesion; (5) abrasion resistance; (6) scratch resistance; and (7) ballistic impact resistance.

Thickness Measurements.

Definition and Significance. A variation in lens thickness from one location to another is an indication that prismatic power and/or refractive power are present in the lens.

Thickness Test Method and Instrument. The physical thickness of the WARDOVE spectacle lenses was measured at five locations, as shown in Figure 2, on each lens using a Vigor GA-725 guage. The Vigor guage is a dial-indicating thickness guage that reads to the nearest 0.01 millimeter.

Thickness Results. The thicknesses measured at the five locations on the WARDOVE spectacles are given in Tables 1 and 2 for the WD1 and WD2 spectacles, respectively. In the tables, the locations are labeled center, in, out, up and down for the left and right lenses. The average thickness of the WARDOVE spectacle lenses was slightly greater than 3 mm. One lens measured over 3.5 mm thick. Variations in thickness measured on the different lenses correlate with the measured prismatic deviation.

Sample	**Thickness (mm)**					Maximum	
	Top	**In**	**Center**	**Out**	**Bottom**	Variation(mm)	
Q01S1							
R	3.11	3.10	3.10	3.10	3.06	0.05	
L	3.19	3.15	3.15	3.17	3.12	0.07	
Q02S1							
R	3.08	3.04	3.11	3.12	3.03	0.09	
L	3.09	3.13	3.12	3.04	3.12	0.09	
Q03S1							
R	3.11	3.12	3.14	3.10	3.14	0.04	
L	3.10	3.09	3.14	3.12	3.13	0.05	
Q04S1							
R	3.19	3.17	3.18	3.11	3.16	0.08	
L	3.22	3.19	3.23	3.21	3.22	0.04	
Q05S1							
R	3.11	3.12	3.13	3.08	3.11	0.05	
L	3.06	3.07	3.06	3.03	3.04	0.04	
Q06S1							
R	3.20	3.18	3.21	3.19	3.19	0.03	
L	3.18	3.16	3.21	3.21	3.20	0.05	
Q07S1							
R	3.21	3.23	3.24	3.21	3.22	0.03	
L	3.18	3.21	3.18	3.13	3.16	0.08	
Q08S1							
R	3.18	3.15	3.17	3.15	3.15	0.03	
L	3.13	3.12	3.15	3.14	3.15	0.03	
Q09S1							
R	3.21	3.19	3.23	3.23	3.21	0.04	
L	3.17	3.18	3.20	3.17	3.21	0.04	
Q10S1							
R	3.05	3.04	3.07	3.02	3.04	0.05	
L	3.12	3.08	3.13	3.13	3.11	0.05	Overall
Max	3.22	3.23	3.24	3.23	3.22	0.09	3.24
Min	3.05	3.04	3.06	3.02	3.03	0.03	3.02
Average	3.14	3.14	3.16	3.13	3.14	0.05	3.14

Table 1: Measured Thicknesses of WARDOVE WD1 Lenses at Five Locations

Sample	Thickness (mm)					Maximum
	Top	In	Center	Out	Bottom	Variation(mm)	
Q01S2							
R	3.24	3.23	3.27	3.23	3.25	0.04	
L	3.14	3.15	3.19	3.14	3.19	0.05	
Q02S2							
R	3.22	3.26	3.27	3.18	3.29	0.11	
L	3.20	3.16	3.23	3.23	3.23	0.07	
Q03S2							
R	3.50	3.41	3.52	3.57	3.50	0.16	
L	3.25	3.24	3.24	3.15	3.15	0.10	
Q04S2							
R	3.27	3.14	3.24	3.27	3.26	0.13	
L	3.25	3.25	3.22	3.13	3.15	0.12	
Q05S2							
R	3.18	3.15	3.19	3.13	3.16	0.06	
L	3.19	3.11	3.18	3.16	3.14	0.08	
Q06S2							
R	3.18	3.12	3.18	3.19	3.15	0.07	
L	3.20	3.15	3.20	3.15	3.18	0.05	
Q07S2							
R	3.19	3.19	3.23	3.18	3.22	0.05	
L	3.15	3.13	3.18	3.14	3.18	0.05	
Q08S2							
R	3.14	3.20	3.20	3.09	3.22	0.13	
L	3.10	3.00	3.17	3.21	3.18	0.21	
Q09S2							
R	3.18	3.14	3.18	3.16	3.18	0.04	
L	3.16	3.14	3.18	3.15	3.15	0.04	
Q10S2							
R	3.20	3.14	3.18	3.17	3.12	0.08	
L	3.20	3.16	3.20	3.15	3.15	0.05	Overall
Max	3.50	3.41	3.52	3.57	3.50	0.21	3.57
Min	3.10	3.00	3.17	3.09	3.12	0.04	3.00
Average	3.21	3.17	3.22	3.19	3.20	0.08	3.20

Table 2: Measured Thicknesses of WARDOVE WD2 Lenses at Five Locations

Cosmetic Quality

Definition and Significance. Cosmetic quality in optical components is defined in terms of defects or imperfections that can be seen upon visual examination. Cosmetic defects in eyewear include small imperfections in the lens material or the protective coating. Defects such as inclusions, bubbles, black specks, waviness, cloudiness, stains, chips, and workmanship or design flaws are classified as cosmetic defects. Imperfections such as inclusions, specks and bubbles can cause visual distraction and may be mistaken for objects. The subjective acceptance of the LEP spectacles can be determined by the cosmetic quality. Many different formal specifications for cosmetic quality exist (ref. MIL-V- XXXX and MIL-V-43511C). The specification and measurement of cosmetic defects is the most subjective of all the optical performance requirements for eyewear. Cosmetic defects are, however, important for user acceptance.

Cosmetic Quality Test Method and Instrument. The WARDOVE spectacle lenses were visually examined in transmission and reflection at a distance of 10 to 20 inches with fluorescent backlighting and a broad diffuse background. The lenses were examined with both light and dark backgrounds. Additionally, the lenses were examined in transmission and reflection under intense illumination from a fiber optic light. The defects that were seen were noted.

Cosmetic Quality Results. Very few flaws were evident in the WARDOVE spectacle lenses under normal backlighting examination. Under intense light, however, numerous small inclusions and what appeared to be flecks of dielectric coating were visible in the laminating layer. Some glue contamination was noted around the edge of some of the lenses. This contamination resulted from the fact that Pilkington used a silicone type of cement around the edges of the lenses to reduce stresses from the frames.

Stresses Evident in Crossed Polarizers

Definition and Significance. Mechanical stresses in polycarbonate lenses are visible when the lens is placed between crossed polarizers. Fringes are visible in areas of stress due to the stress-induced birefringence. Stress in laminated lenses such as the WARDOVE spectacle lenses can cause delamination to occur, especially under varying temperature conditions.

Stress Test Method and Instrument. A light table was covered with a sheet of polarizing material. The WARDOVE spectacles were placed on the polarized light table and examined through another sheet of polarizing material. Photographs were taken.

Stress Results. A few of the WARDOVE lenses evidenced small stress areas at the edge of the lenses where the lens mounts in the frame. Figure 4 shows an example of two of the WARDOVE spectacles viewed in the polarization tester. Note the slight concentration of fringes at the edges of the lenses, especially at the upper nasal region of the right lenses (lenses on left side of the figure). Similar minor stress areas were noted on most of the WARDOVE lenses.

Hardcoating Adhesion

Definition and Significance.. In order to provide scratch and abrasion resistance to the soft polycarbonate LEP lenses, a well-adhered hard coating is required. The durability and adhesion of the hard coatings on polycarbonate LEP is important to increase the operational life. No

adhesion requirement for the hard coatings is specified in MIL-V-43511C, but a stringent coating adhesion requirement is recommended for LEP because of the high unit cost.

Coating Adhesion Test Method and Instrument. Tape test method B as defined in ASTM D3359-83 was used to test one of the WARDOVE lenses of each coating type. This test consists of cutting a lattice pattern in the coating and applying and removing pressure-sensitive tape in that area. Graded levels of results, from 5B (best) to 0B (worst), are given in the method. Adhesion tests were performed on the front and rear side of the lenses. Only one lens of each type was tested because of the limited number of available samples and the destructive nature of the test.

Coating Adhesion Results. Both sides of the WD1 and the WD2 lenses tested rated the highest adhesion (5B) defined in ASTM 3359-83.

Abrasion Resistance

Definition and Significance. The hard coating of LEP spectacles and visors must resist abrasion due to the rubbing of various materials on the surface. The hard coating must withstand numerous and repeated cleanings with either paper tissues or special micro-fiber clothes. During use the LEP may be rubbed by other materials, such as the helmet bag, flight suit or flight gloves. Numerous different tests are defined in military and commercial standards that can be used to measure the abrasion resistance of the LEP hard coating. It is essential to measure the abrasion resistance of the hard coating as applied to a completed lens and not a sample coupon. The abrasion test must, therefore, be compatible with the curved surface of the LEP lenses. Aabrasion resistance is defined in terms of increase in haze. MIL-V-85374 Amendment 1 (Jan. 1981) requires that the increase in haze after abrasion testing, as measured by the method defined in ASTM D1003-92, shall be not more than 6% and the decrease in transmission not more than 4%.

Abrasion Resistance Test Method and Instrument. The abrasion resistance of the coating on one WARDOVE lens of each coating type was tested using the eraser test defined in MIL-V-85374 Amendment 1 (Jan. 1981), modified to be consistent with the measurement method specified. The area of the lens where the abrasion test was to be performed was identified. The haze in this area was measured before the abrasion test using the BKY Gardner XL-211 hazemeter. A standard, specified, eraser under a 2 to 2.5 pound load was rubbed on the coating for 20 cycles (motion of the eraser up and back is one cycle), with a stroke length of approximately 1." For each area of the lens tested the .264" diameter eraser was rubbed 20 cycles in three adjacent locations so as to cover an area as large as the aperture of the measuring instrument (an area of approximately .8 x 1 inch was rubbed). The surface was cleaned and the haze was measured again.

Abrasion Resistance Results. Both WD1 and WD2 lenses exceeded the requirements of MIL-V-85374. Measured haze values on both types of WARDOVE lenses were less than 2.5% after abrasion testing.

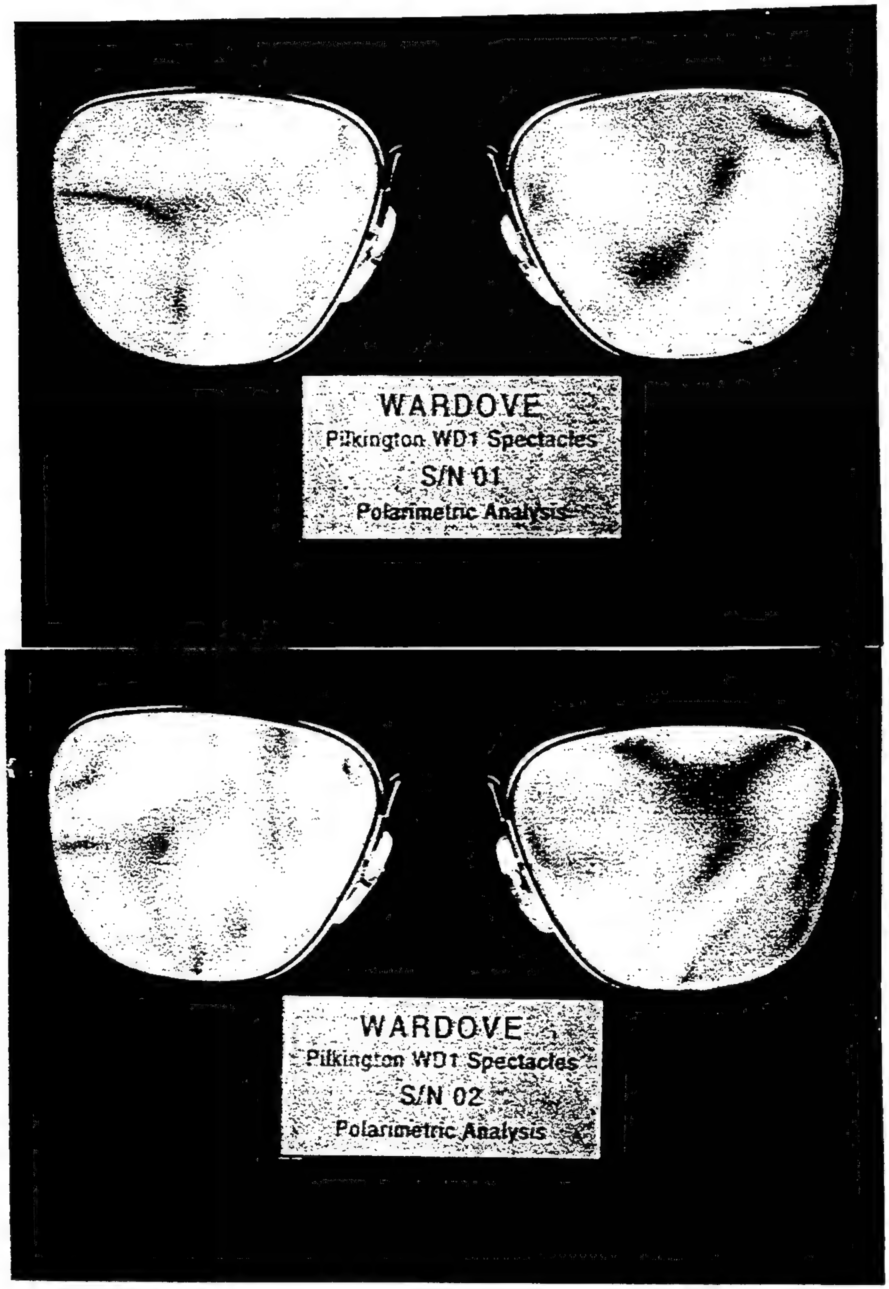


Figure 4: WARDOVE Spectacles Viewed Between Crossed Polarizers.

Scratch Resistance

Definition and Significance. The studies performed during the AAVP program found that the only reason that pilot helmet visors are removed from service is due to scratches in the surfaces of the visors (Ref. AL/OE-TR-1996-0117). Improvement of the scratch resistance of the hard coating of LEP will result in an increased usable life and thus a direct reduction of the life-cycle costs. Currently requirements, specifications and test methods exist for measuring the abrasion resistance of the hard coatings on military eyewear, but no specific requirement for scratch resistance exists. Although abrasion resistance and scratch resistance are related, completely different mechanisms produce scratches than produce abrasions. In abrasion tests, a specified abrasive material is rubbed on the surface being tested with a prescribed force and motion. The motion is often back and forth or circular for a prescribed number of cycles. The criteria for passing or failing the test vary from visual inspection to measurement of the percent of increase in light scattered by the surface. The mechanism for producing scratches on a surface differs from the mechanisms that produce abrasions. A scratch occurs when a sharp, hard object is dragged across the surface of the visor with a force pressing the sharp object against the surface. This is often a single event that produces a single scratch on the surface. Multiple occurrences of this type of single event produce multiple scratches. It is often implied that the abrasion resistance of a surface is representative of the scratch resistance. This is not necessarily true. The scratch resistance of WARDOVE spectacle lenses is measured in terms of the MSRT (discussed below). An MSRT value of 80 (adjusted to MSRT S/N001, Stylus 3) or greater is desirable for military LEP.

Scratch Resistance Test Method and Instrument. A new method and apparatus for directly determining the scratch resistance of the hard coatings on polycarbonate lenses and visors was developed and initial tests of the method were performed during the Armstrong Laboratory AAVP program.(Ref. AL/OE-TR-1996-0140). The new method is the Maier Scratch Resistance Tester (MSRT). The MSRT produces the scratching mechanism in a controlled manner such that the scratch resistance of the surface can be determined directly. Although the MSRT has not, as yet, been qualified as an absolute measure, it has been demonstrated to be a reliable means of measuring the relative level of scratch resistance of visor hard coatings. MSRT S/N001, Stylus 3 was used to test the scratch resistance of one of each type of the WARDOVE spectacle lenses. The stylus tip that was used for testing the WARDOVE lenses is a .0781" diameter right cylinder at an angle of 60° from the horizontal plane. The design and operation of the MSRT is completely described and the results of initial testing of visor hard coatings are given in AL/OE TR-1996-0140. The MSRT apparatus for scratch resistance testing is illustrated in several views in Figure 5. The apparatus consists of a stylus (1) that is free to slide up and down in the stylus guide (2) of the stylus guide block (3). The stylus can have various types of tips (4) depending on the particular test that is desired. The tip of the stylus can be of different designs such that the scratching mechanism that is expected in the use of the surface can be approximated. The stylus is pushed down by the force of its own weight onto the surface being tested. The guide block has wheels (5) attached that permit it to be easily rolled across the surface under test. The guide block has a handle (6) attached that permits the operator to hold the apparatus and to pull it across the surface being tested. Different weights (7) can be placed on the upper end of the stylus to vary the force with which the stylus tip is pressed against the surface being tested. A milled guide in the side of the stylus shaft prevents the stylus from rotating as it is dragged across the

surface. To operate the scratch resistance tester, the wheels of the apparatus are placed on the surface to be tested such that the stylus is vertical. The stylus slides in the stylus guide so that the force of the weight of the stylus is applied to the stylus tip which is resting on the surface. The handle is used to pull the apparatus in a straight-line motion such that the wheels roll on the surface and the tip of the stylus drags across the surface. The stylus is kept in a vertical direction during the dragging. A single dragging of the stylus tip is performed. The distance through which the stylus is dragged will depend on the surface being tested. The length of the drag should be .5 to 1.0 inches, if possible. The surface is then examined visually to ascertain whether or not it was scratched. If no scratch has occurred, a weight is added to the stylus and the dragging operation is performed again in a different position on the surface. The weight is increased until a scratch occurs. The criteria for occurrence of a scratch on the visor surface is any scratch that is detectable with the unaided eye under ideal lighting conditions. The MSRT value is the weight, in grams, which must be added to the stylus to just produce a visible scratch.

Scratch Resistance Results. The scratch resistance of the hard coating on the front and back sides of one WD1 and one WD2 lens was measured. Only one lens was tested because of the limited supply of WARDOVE samples and the destructive nature of the test. The MSRT value for the front surface of the WD1 lens was 90 and the MSRT value for back surface was 115. The MSRT value for the front surface of the WD2 lens was 80 and the MSRT value for back surface was 100. These MSRT values indicate that the hard coatings tested are sufficiently resistant to scratches.

Ballistic Impact Resistance

Definition and Significance. Ballistic impact resistance of eyewear is required to prevent eye damage from flying particles or objects. Polycarbonate material, such as the material of the WARDOVE spectacle lenses, is inherently impact resistant because it is flexible. Upon impact the polycarbonate will elastically flex rather than breaking. A well-adhered hard coating (or reflective dielectric coating) can, however, make the polycarbonate brittle. The hard coating and the dielectric coating for LEP eyewear must be well adhered and resist abrasion and scratches while not degrading the ballistic impact resistance. The ballistic impact resistance is typically defined in terms of a specified projectile impacting the lens at a specified velocity. No ballistic impact resistance requirements were placed on the WARDOVE spectacles since the lenses are mounted in frames that are not safety frames.

Ballistic Impact Test Method and Instrument. Ballistic impact resistance tests were performed on two lenses, each having one type of WARDOVE coating. The test method used was the ball drop test defined in ANSI 80.1-1995. The test consists of dropping a 5/8 inch diameter, 16-gram steel ball from a height of 50 inches onto the lens while it is supported in a prescribed manner.

Ballistic Impact Results. The two WARDOVE spectacle lenses tested did not shatter, break or crack in the ball drop test. No damage occurred to the polycarbonate lenses. Damage was, however, evident in the dielectric coating contained in the lamination layer. The dielectric coating cracked where the ball impacted the lens. This cracking of the reflective dielectric coating is significant in that the laser protection provided by this area would be altered. The cracking of

the dielectric coating occurred because the polycarbonate lens flexed at the point of impact. This is of some concern for the visors with the same dielectric coating since the visor may be flexed in the process of putting it on the helmet or in normal use.

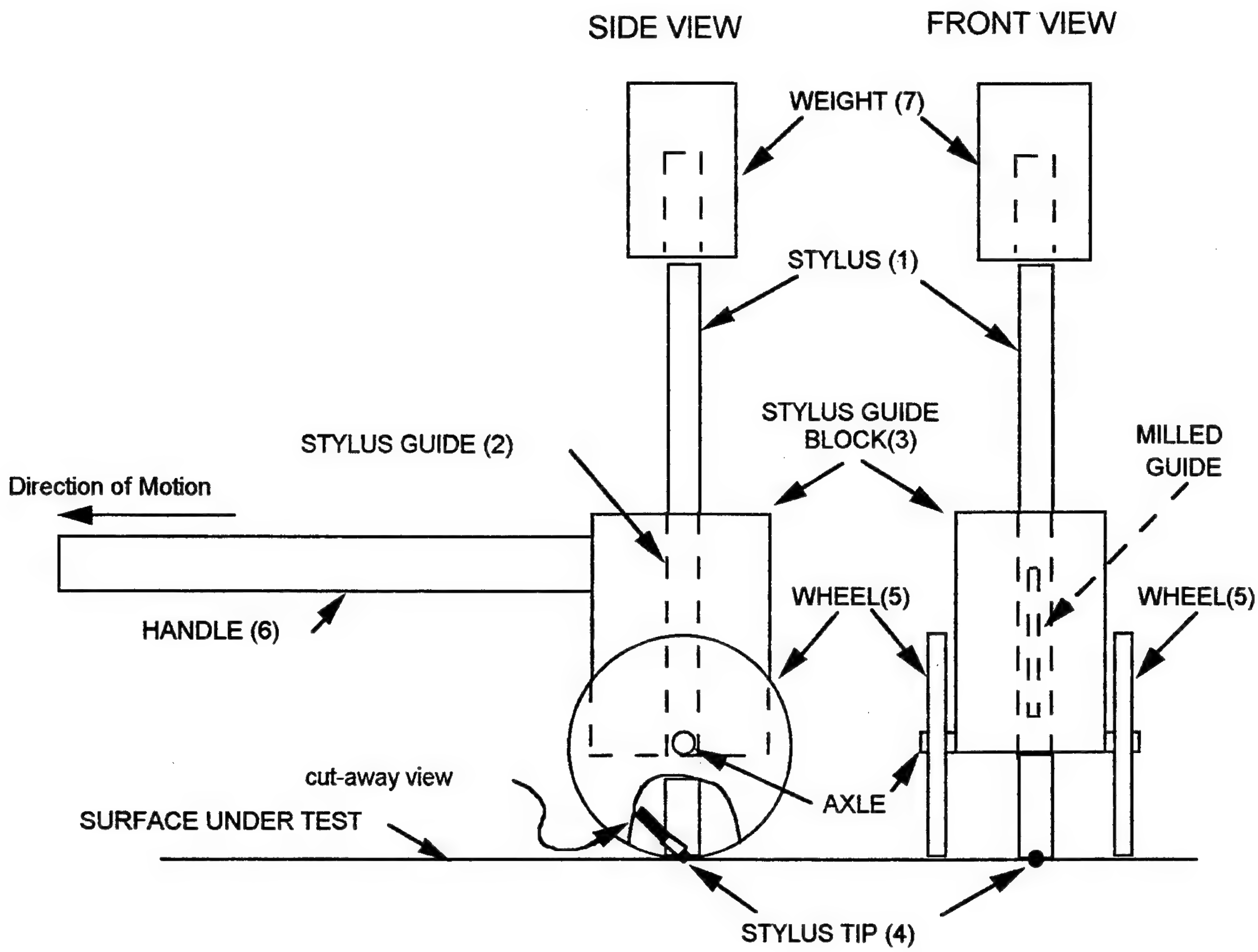


Figure 5: Schematic Illustration of the Maier Scratch Resistance Tester.

Optical Quality

The optical quality parameters that were measured on the WARDOVE spectacle samples included: (1) prismatic deviation; (2) refractive power; (3) distortion; and (4) haze.

Prismatic Deviation

Definition and Significance. Prismatic deviation is a measure of the angular deviation of light from a straight-line path through the spectacle lenses. Prismatic deviation is caused by prismatic power which results from non-parallel surfaces of the lenses, variations in refractive index, dissimilar curvatures of the front and back surfaces, or a combination of these effects. The unit of measure for prismatic power is a prism diopter. One prism diopter (D) causes a one centimeter deflection of a target at a distance of one meter, or 1 diopter (prismatic power) = 10 milliradians of angular deviation. Angular deviation of the light as it passes through eyewear can cause objects to appear at displaced locations. Differences in the prismatic deviation at the two different locations through which the left and right eyes view can cause problems of binocular disparity. If the differences in prismatic deviation at the two eye locations are too large, eye-strain and headaches can result. The eyes will naturally rotate in opposite directions horizontally toward the nose to focus on close objects and to merge the image of an object. The eyes rotate in the same direction horizontally and vertically to change the direction of viewing. If the angular deviation for the two eyes is the same and in the same direction, the eyes will easily merge the image but an apparent displacement of the object location will result. If the angular deviation for the two lenses is different or in the opposite direction, eye-strain and fatigue can occur. The vertical and horizontal prismatic deviations of the WARDOVE spectacles were measured at the eye-centered locations on each lens. Because of the nature of prismatic deviation, it is important that it be measured as worn and that the magnitude and direction of the prism be measured at each eye location for comparison.

Vertical prismatic deviation. Vertical prismatic deviation causes the apparent location of a target to be up or down from its actual location. The vertical prismatic deviation is designated as positive (+) for base up prism (target apparent location moves down) and negative (-) for base down prism (target apparent location moves up). MIL-V-43511C requires that the vertical prism not exceed 0.18 diopters for any lens and the algebraic difference between the vertical prismatic deviation for the two lenses should not be more than 0.18 diopters.

Horizontal prismatic deviation. Horizontal prismatic deviation causes the apparent location of the target to be left or right of its actual location. Horizontal prismatic deviation is designated positive (+) for base out prism (deflection of target to the right for the left lens as worn, and deflection of the target to the left for the right lens as worn). It is designated negative (-) for base in prism (deflection of the target to the left for the left lens as worn, and deflection of the target to the right for the right lens as worn). MIL-V-43511C requires that the horizontal prism not exceed 0.18 diopters for any lens. The algebraic sum of the horizontal prismatic deviation for the right and left lenses should not exceed 0.50 diopters. The algebraic difference between the horizontal prismatic deviation should not exceed 0.18 diopters.

Prism Test Method and Instrument. The instrument that was used for measuring the prismatic deviation for the WARDOVE spectacles is illustrated in Figure 6. In this instrument a

Davidson D-275 focusing telescope is used to view a grid pattern through the spectacle lenses. The distance of the grid pattern from the spectacle lens was set at 50 inches. A 20 square-per-inch grid (.05 inch line spacing) was used. Thus, each grid line represented .1 diopters of prismatic deviation at the 50 inch distance. With the Davidson D-275 telescope, a .02 diopter resolution can be achieved. The location of the telescope line of sight without the lens was compared with the location with the lens in place (as worn). The amount of displacement of the line of sight caused by the lens divided by the distance of the lens to the grid is the prismatic deviation in radians. The magnitude and direction (prism base direction) of the prismatic deviation was recorded for the vertical and horizontal directions. The algebraic sums and differences of the prism measured on two lenses in a pair of spectacles were computed.

Prismatic Deviation Results. The measured values of the prismatic deviations in the horizontal and vertical directions for all of the WARDOVE lenses are given in Tables 3 and 4 for the WD1 and the WD2 samples, respectively. The sums and differences of the prismatic deviations for each pair of spectacle lenses are also given in the tables. Several of the WD1 lenses evidenced prism in excess of the recommended amount. Most of the WD2 spectacles had more prism than is recommended. The amount of prism evident in the WARDOVE samples will probably not cause significant vision problems, but should be noted during evaluation of the vision test results.

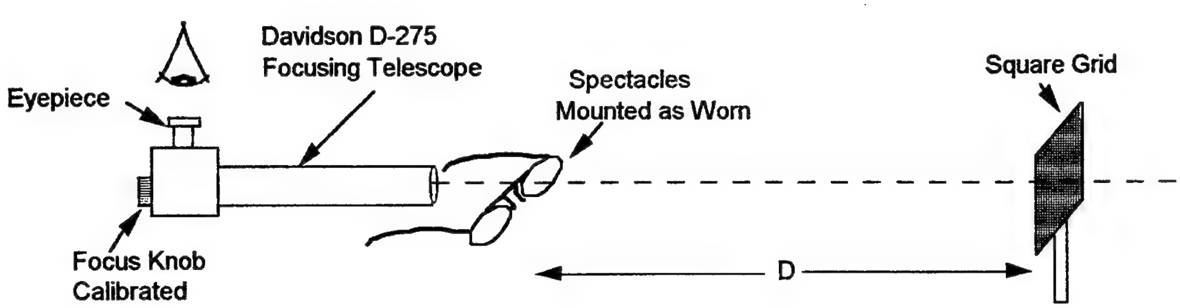


Figure 6: Schematic Illustration of Telescope Method for Measuring Prismatic Deviation and Refractive Power.

Refractive Power

Definition and Significance. Refractive power is the lensing (focusing or defocusing) effect produced by an optical element. Positive refractive power converges or focuses the light and is designated as (+). Negative refractive power diverges or defocuses the light and is designated as (-). The power of a lens in diopters is the reciprocal of the focal length in meters. A two-meter focal length lens would thus have 0.5 diopters of power. Ideally, the WARDOVE spectacle lenses should be made to have no optical power. The lenses can, however, have spherical power

or astigmatic power (power in one meridian) due to differences in curvature of the two surfaces or from differences in thickness of the laminating layer. If a lens has negative refractive power the eyes will have to accommodate in order to focus. If the lens has positive power, distant objects will be out of focus for the emmetropic (normal) eye. Differences in optical power in the different meridians can cause blurring of the image. Spherical and astigmatic power can cause eye strain and loss of acuity. Because of the nature of refractive power, it is important that it be measured on the spectacles as worn. MIL-V-43511C requires that the spherical refractive power not exceed plus or minus 0.13 diopters for any lens and that refractive power in the vertical or horizontal meridians should be less than plus or minus .13 diopters. The difference in the refractive power for the horizontal and vertical meridians should less than .13 diopters. ANSI Z87.1 89 requirements for refractive power are more stringent. ANSI requires that the spherical power, the astigmatic power and the difference in the refractive power for the horizontal and vertical meridians be less than 0.06 diopters.

Refractive Power Test Method and Instrument. The instrument described above for measuring the prismatic deviation (Figure 6) was also used to measure refractive power. The focusing mechanism (knob) of the Davidson D-275 telescope was calibrated in diopters using lenses of known powers. The horizontal and vertical grid lines were brought into focus while viewing through the spectacle lenses and the lens power was read from the telescope focus knob. Since the refractive power of the WARDOVE lenses should be very small, a standard ophthalmic lensometer is not an acceptable instrument for measuring refractive power unless it is capable of measuring refractive power of .03 diopter or less.

Refractive Power Results. The measured values of the refractive power in the horizontal and vertical directions for all of the WARDOVE lenses are given in Tables 3 and 4 for the WD1 and the WD2 samples, respectively. The astigmatic power, the difference in power of the two meridians of the same lens, is computed and given in the tables. The difference of power in the horizontal and vertical meridians between the two lenses in each pair of spectacles is computed and given in the tables. Three of the WD1 lenses had slightly higher than the recommended refractive power. All of the WD2 lenses were within military and ANSI recommended values.

Sample	Distort.	Gardner 211				Hazegard Plus			Power(diopters)					Prism (diopters)				
		Trans.	Raw H.	%Haze	Adjustd	Trans.	Haze	Clar.%	Vert.	Horz.	Astig.	V Diff	H Diff	Up/down	In/out	H Sum	H Diff	V Diff
Q01S1																		
R	P1	82.3	1.02	1.24	1.29	86.1	1.42	99.8	-0.03	-0.03	0.00			-0.02	0.21			
L	P2	82.5	1.14	1.38	1.43	85.8	1.51	99.7	-0.09	-0.11	0.02			0.01	0.17			
Average		82.4	1.08	1.31	1.36	86.0	1.47	99.8				0.06	0.08			0.38	0.04	-0.03
Q02S1																		
R	P1	78.8	1.21	1.54	1.60	82.9	1.88	99.7	-0.03	-0.01	-0.02			-0.23	0.31			
L	P1	78.4	1.49	1.90	1.97	82.6	2.14	99.8	0.00	0.00	0.00			-0.13	0.03			
Average		78.6	1.35	1.72	1.79	82.8	2.01	99.8			-0.01	-0.03	-0.01			0.34	0.28	-0.10
Q03S1																		
R	P1	79.1	1.19	1.50	1.57	83.9	1.73	99.8	-0.01	-0.17	0.16			-0.16	0.11			
L	P1	79.2	1.23	1.55	1.62	83.2	1.85	99.8	0.00	0.22	-0.22			-0.17	0.24			
Average		79.2	1.21	1.53	1.59	83.6	1.79	99.8			-0.03	-0.01	-0.39			0.35	-0.13	0.01
Q04S1																		
R	P1	78.3	1.32	1.69	1.76	82.9	1.85	99.7	-0.02	-0.02	0.00			0.05	0.07			
L	P1	77.9	1.45	1.86	1.93	82.3	2.10	99.8	0.01	0.01	0.00			-0.10	0.16			
Average		78.1	1.39	1.77	1.84	82.6	1.98	99.8			0.00	-0.03	-0.03			0.23	-0.09	0.15
Q05S1																		
R	P2	78.3	1.52	1.94	2.01	82.7	2.14	99.8	0.02	0.02	0.00			-0.07	-0.03			
L	P1	79.0	1.35	1.71	1.78	83.3	1.92	99.8	-0.01	-0.02	0.01			-0.04	0.11			
Average		78.7	1.44	1.82	1.89	83.0	2.03	99.8			0.01	0.03	0.04			0.08	-0.14	-0.03
Q06S1																		
R	P1	82.6	1.12	1.36	1.41	86.1	1.58	99.8	0.00	-0.01	0.01			-0.02	0.18			
L	P2	77.9	1.30	1.67	1.74	82.2	1.63	99.8	0.01	0.00	0.01			-0.18	0.27			
Average		80.3	1.21	1.51	1.57	84.2	1.61	99.8			0.01	-0.01	-0.01			0.45	-0.09	0.16
Q07S1																		
R	P1	78.1	1.14	1.46	1.53	82.8	1.74	99.8	0.04	-0.01	0.05			-0.08	0.08			
L	P2	78.2	1.33	1.70	1.77	82.6	1.97	99.8	0.03	0.00	0.03			-0.02	-0.02			
Average		78.2	1.24	1.58	1.65	82.7	1.86	99.8			0.04	0.01	-0.01			0.06	0.10	-0.06
Q08S1																		
R	P1	85.6	1.21	1.41	1.46	90.2	1.27	100.0	-0.04	-0.02	-0.02			-0.02	0.21			
L	P1	85.0	1.19	1.40	1.44	89.7	1.53	99.8	-0.08	-0.02	-0.06			-0.12	0.22			
Average		85.3	1.20	1.41	1.45	90.0	1.40	99.9			-0.04	0.04	0.01			0.43	-0.01	0.10
Q09S1																		
R	P1	81.8	1.32	1.61	1.67	85.7	1.79	99.8	0.03	-0.01	0.04			-0.06	0.28			
L	P1	82.8	1.13	1.36	1.42	86.5	1.56	99.8	-0.02	-0.17	0.16			-0.17	0.11			
Average		82.3	1.23	1.49	1.54	86.1	1.68	99.8			0.10	0.05	0.16			0.39	0.17	0.11
Q10S1																		
R	P1	78.2	1.54	1.97	2.04	82.3	2.24	99.8	-0.05	-0.05	0.00			0.01	0.14			
L	P1	78.3	1.53	1.95	2.02	82.6	2.16	99.8	0.01	0.00	0.01			-0.06	0.27			
Average		78.3	1.54	1.96	2.03	82.5	2.20	99.8				-0.06	-0.05			0.41	-0.13	0.07
Max		85.60	1.54	1.97	2.04	90.20	2.24	100.00	0.04	0.22	0.16	0.06	0.16	0.05	0.31	0.45	0.28	0.16
Min		77.90	1.02	1.24	1.29	82.20	1.27	99.70	-0.09	-0.17	-0.22	-0.06	-0.39	-0.23	-0.03	0.06	-0.14	-0.10
Average		80.12	1.29	1.61	1.67	84.32	1.80	99.80	-0.01	-0.02	0.01			-0.08	0.16			

Table 3: Optical Properties of WD1 WARDOVE Spectacle Lenses

Sample	Distort.	Gardner 211				Hazegard Plus			Power(diopters)					Prism(diopters)				
		Trans.%	Raw H.	%Haze	Adjustd	Trans.%	Haze	Clar.%	Vert.	Horz.	Astig.	V Diff	H Diff	Up/down	In/out	H Sum	H Diff	V Diff
Q01S2																		
R	P1	85.5	1.05	1.23	1.27	87.5	1.40	100.0	0.01	0.01	0.00			-0.12	0.12			
L	P1	85.1	1.07	1.26	1.30	87.2	1.43	100.0	0.04	0.04	0.00			-0.20	0.15			
Average		85.3	1.06	1.24	1.29	87.4	1.42	100.0			0.00	-0.03	-0.03			0.27	-0.03	0.08
Q02S2																		
R	P1	87.3	1.27	1.45	1.49	89.8	1.59	99.7	0.01	0.05	-0.04			-0.15	0.06			
L	P1	85.5	1.32	1.54	1.59	87.9	1.58	99.8	0.03	0.02	0.01			-0.12	0.27			
Average		86.4	1.30	1.50	1.54	88.9	1.59	99.8			-0.02	-0.02	0.03			0.33	-0.21	-0.03
Q03S2																		
R	P1	85.4	1.17	1.37	1.41	87.4	1.50	99.8	0.07	0.05	0.02			-0.01	0.48			
L	P1	85.0	1.12	1.32	1.36	86.9	1.46	99.7	0.04	0.06	-0.02			0.15	-0.08			
Average		85.2	1.15	1.34	1.39	87.2	1.48	99.8			0.00	0.03	-0.01			0.40	0.56	-0.16
Q04S2																		
R	P1	85.3	1.20	1.41	1.45	87.0	1.59	99.6	0.04	0.04	0.00			0.10	0.44			
L	P1	87.0	1.06	1.22	1.26	89.1	1.32	99.7	0.05	0.06	-0.01			0.14	-0.07			
Average		86.2	1.13	1.31	1.35	88.1	1.46	99.7				-0.01	-0.02			0.37	0.51	-0.04
Q05S2																		
R	P1	85.8	1.28	1.49	1.53	88.1	1.63	99.8	0.01	0.02	-0.01			-0.06	0.04			
L	P1	86.4	1.36	1.57	1.61	88.6	1.77	99.8	0.00	-0.01	0.01			0.01	0.25			
Average		86.1	1.32	1.53	1.57	88.4	1.70	99.8			0.00	0.01	0.03			0.29	-0.21	-0.07
Q06S2																		
R	P1	86.0	1.46	1.70	1.74	88.1	1.18	99.8	0.01	0.02	-0.01			0.02	0.30			
L	P1	85.8	1.18	1.38	1.42	88.1	1.13	99.8	0.03	0.04	-0.01			-0.03	0.17			
Average		85.9	1.32	1.54	1.58	88.1	1.16	99.8			-0.01	-0.02	-0.02			0.47	0.13	0.05
Q07S2																		
R	P1	86.1	1.22	1.42	1.46	88.3	1.47	99.8	0.06	0.02	0.04			-0.12	0.20			
L	P1	86.0	1.22	1.42	1.46	88.0	1.55	99.8	0.02	0.04	-0.02			-0.14	0.14			
Average		86.1	1.22	1.42	1.46	88.2	1.51	99.8			0.01	0.04	-0.02			0.34	0.06	0.02
Q08S2																		
R	P1	87.0	1.13	1.30	1.34	89.1	1.47	99.5	0.05	0.05	0.00			-0.36	-0.02			
L	P1	87.1	1.06	1.22	1.25	89.2	1.37	99.5	0.00	0.01	-0.01			-0.22	0.47			
Average		87.1	1.10	1.26	1.30	89.2	1.42	99.5				0.05	0.04			0.45	-0.49	-0.14
Q09S2																		
R	P1	85.7	1.34	1.56	1.61	88.0	1.72	99.8	0.02	0.03	-0.01			-0.05	0.23			
L	P1	85.9	1.30	1.51	1.55	88.1	1.67	99.8	0.03	0.01	0.02			-0.07	0.17			
Average		85.8	1.32	1.54	1.58	88.1	1.70	99.8			0.01	-0.01	0.02			0.40	0.06	0.02
Q10S2																		
R	P1	86.1	1.30	1.51	1.55	88.2	1.49	99.8	0.02	0.01	0.01			0.10	0.29			
L	P1	86.0	1.33	1.55	1.59	88.1	1.51	99.8	0.01	0.05	-0.04			-0.02	0.06			
Average		86.1	1.32	1.53	1.57	88.2	1.50	99.8			-0.02	0.01	-0.04			0.35	0.23	0.12
Max		87.30	1.46	1.70	1.74	89.80	1.77	100.00	0.07	0.06	0.04	0.05	0.04	0.15	0.48	0.47	0.56	0.12
Min		85.00	1.05	1.22	1.25	86.90	1.13	99.50	0.00	-0.01	-0.04	-0.03	-0.04	-0.36	-0.08	0.27	-0.49	-0.16
Average		86.00	1.22	1.42	1.46	88.14	1.49	99.77	0.03	0.03	0.00			-0.06	0.18			

Table 4: Optical Properties of WD2 WARDOVE Spectacle Lenses

Distortion

Definition and Significance. Distortion, as defined in MIL-V-43511C, results from localized deviation of light. This can be caused by localized variations of refractive index, or variations in the thickness of the lens or the protective coating. Distortion, in this context, is the common definition of distortion meaning misshapen or twisted out of natural, normal or original shape. This is not the definition of distortion (one of the five primary monochromatic aberrations) which is found in texts on optics. Eyewear that has distortion can cause reduction in visual acuity and eyestrain, as well as being subjectively disturbing. Distortion is defined in several MILSPECS in terms of patterns which result when viewing through the visor in a specified "distortion tester" referred to as an Ann Arbor Tester (manufactured by Ann Arbor Optical Co. -Ref. MIL-V-43511C). The "distortion tester" described in Figure 3 of MIL-V-43511C is a double-pass Ronchi test in which a 60-line per inch Ronchi ruling is used. Figure 1, Visor Distortion Standards, of MIL-V-43511C shows nine distortion test patterns. The figure from MIL-V-43511C is provided as Figure 7 below. The pattern produced in the tester with eyewear being tested is compared to the nine patterns in Figure 7. The first five patterns (numbered 1 to 5) are acceptable and the remaining four patterns (numbered 6 to 9) are unacceptable. Thus, distortion is defined by MIL-V-43511 in terms of the test patterns given. This test is very subjective and not well defined.

Distortion Test Method and Instrument. The double pass method of measuring distortion defined in MIL-V-43511C was found to be unsatisfactory in the testing of most LEP. Requiring light to pass through the LEP twice reduced the contrast to the point that accurate measurements could not be made. A modified form of the distortion tester defined in MIL-V-43511C was used to evaluate LEP because of the relatively low overall transmittance for LEP, especially LEP intended for day use. A single pass Ronchi optical distortion tester, illustrated in Figure 8, was used to evaluate the WARDOVE spectacles. This Ronchi tester consists of two 50-line per inch Ronchi rulings (clear plates with equally spaced black lines), two high quality lenses, a light source and the mechanical mounts for holding and adjusting the components. A CCD camera was used to view the Ronchi pattern, and a video frame grabber and printer were used to record the Ronchi pattern. The Ronchi tester lenses are 63mm diameter, 356 mm focal length telescope objective lenses (Edmund Scientific part No. 031401). A fiber optic light source illuminates the Ronchi rulings located at the focal length of the collimating lens. The second lens collects the light from the collimating lens and projects the illuminated Ronchi ruling onto the second Ronchi ruling. The ruling lines of the two Ronchi rulings are aligned to be parallel. The distance between the second Ronchi ruling and the collecting lens is adjusted to approximately 444 mm to give 10 lines per inch (at the sample plane) in the Ronchi pattern (no sample in place). The pattern consisting of line fringes is viewed through the second Ronchi ruling. The eyewear being tested is placed in the sample plane, located between the collimating and collecting lenses, and the Ronchi pattern is viewed. The Ronchi pattern is compared to the patterns shown in Figure 7. The Ronchi pattern is a form of Moiré' pattern. The fringes of the Ronchi pattern that are viewed result from a beat frequency between the lines on the viewing Ronchi ruling and the lines of the projected Ronchi ruling. If the light in the sample plane is deviated in a direction perpendicular to the ruling lines, a shift in the fringes occurs. If the deviation of light is localized in space, the shift in the fringe is localized. The deviation of the Ronchi fringes from straight lines is, thus, a measure of the amount of localized light deviation that has occurred through the sample. It

should be noted that the Ronchi test only measures light deviations in the direction perpendicular to the ruling lines. If the ruling lines are vertical, only horizontal deviations will effect the pattern. Introducing a sample with optical power in the sample plane will cause the spacing of the fringes to change. Only optical power in the direction perpendicular to the rulings will effect the fringe spacing. If it is desired to measure light deviation or optical power in a particular direction, both of the Ronchi rulings must be rotated so as to remain parallel to each other but perpendicular to the desired axis of measurement. For the distortion testing of the WARDOVE spectacles the Ronchi rulings were oriented vertically. The Ronchi test can be a very sensitive measure of optical distortion. Test sensitivity is determined by the line spacing on the Ronchi rulings and the focal lengths of the lenses. Each fringe of the Ronchi pattern represents an amount of angular deviation of light. The fringe spacing, which is adjusted by changing the separation distance between the second Ronchi ruling and the collecting lens, does not change (to the first approximation) the sensitivity of the instrument. Since a given amount of light deviation is measured by the fringe displacement relative to the fringe spacing, the ability to detect small fringe displacements improves for widely spaced fringes. This gives an apparent, but not actual, increase in sensitivity. In the apparatus described, a deflection of 1.14 milliradians (.114 prism diopters) represents one fringe. Since 1/10 of a fringe displacement can be easily detected, the sensitivity is approximately .01 prism diopters.

Distortion Results. Ronchi patterns produced by the WARDOVE lenses in the above instrument were recorded and compared to the patterns shown in Figure 7. A rating of P1 through P5 (passing) or F6 through F9(failing) were given to the lenses. P1 is the best rating (least distortion) and F9 is the worst rating. All WARDOVE lenses were rated either P1 or P2. Tables 3 and 4 provide a listing of the distortion ratings for each of the WD1 and WD2 lenses respectively. Figure 9 is an example of the Ronchi pattern that was recorded for each lens.

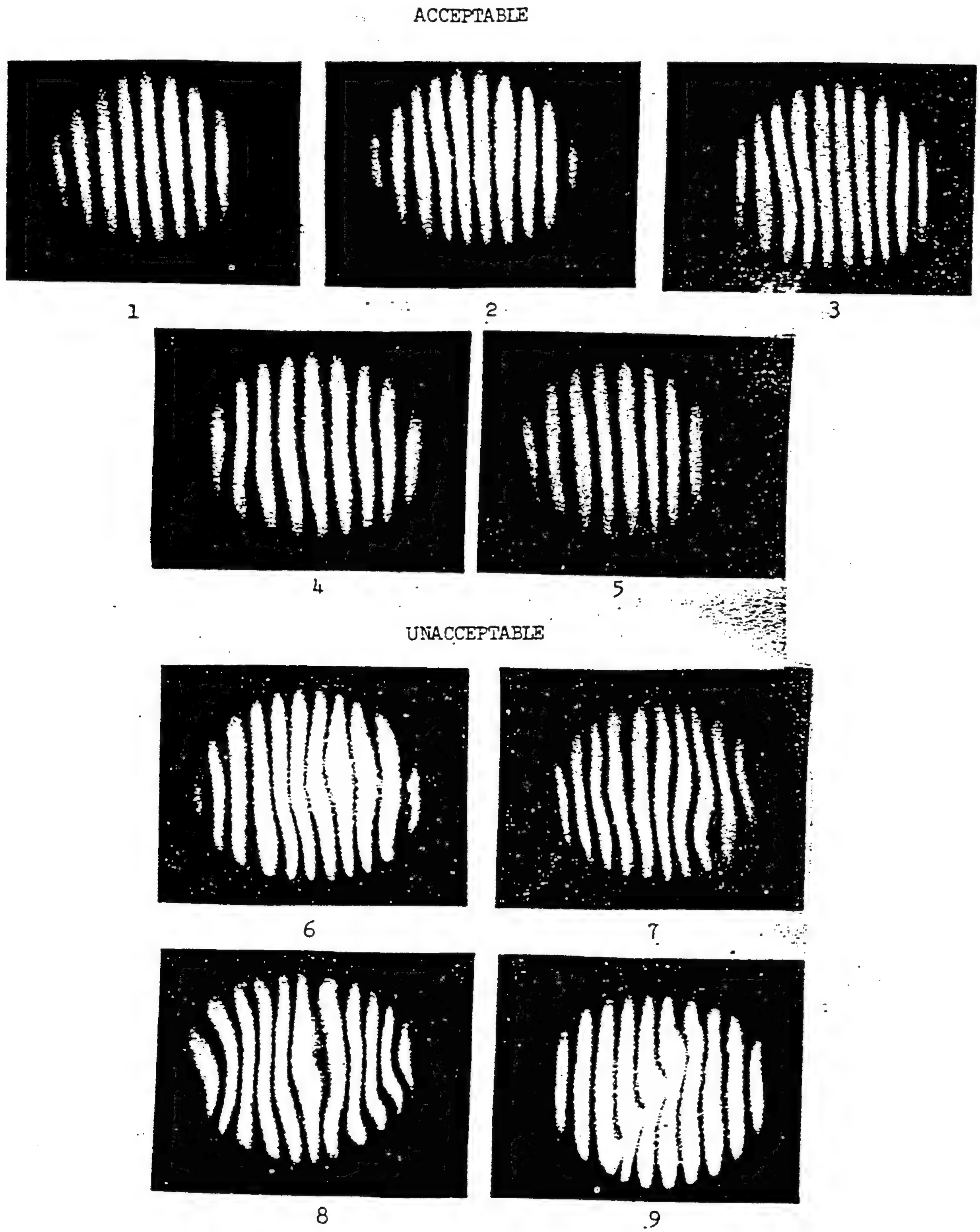


Figure 7: Visor Distortion Standards from MIL-V-43511C.

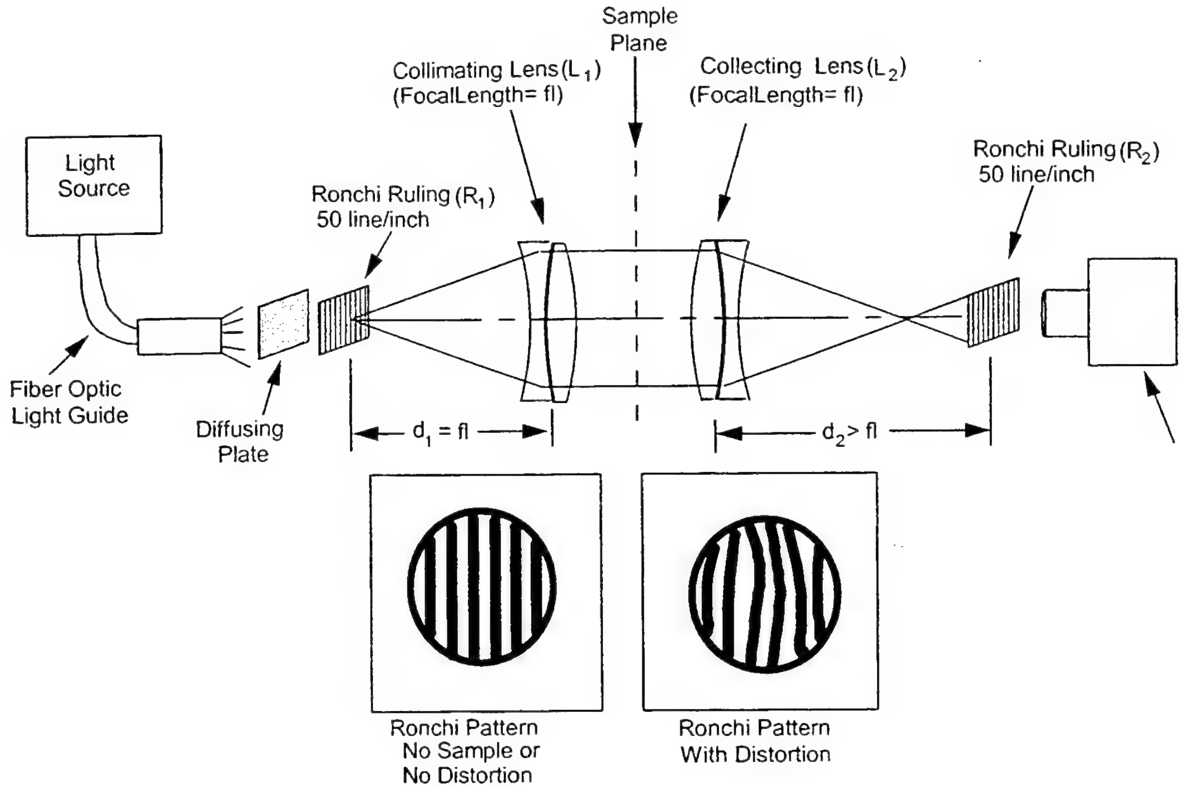
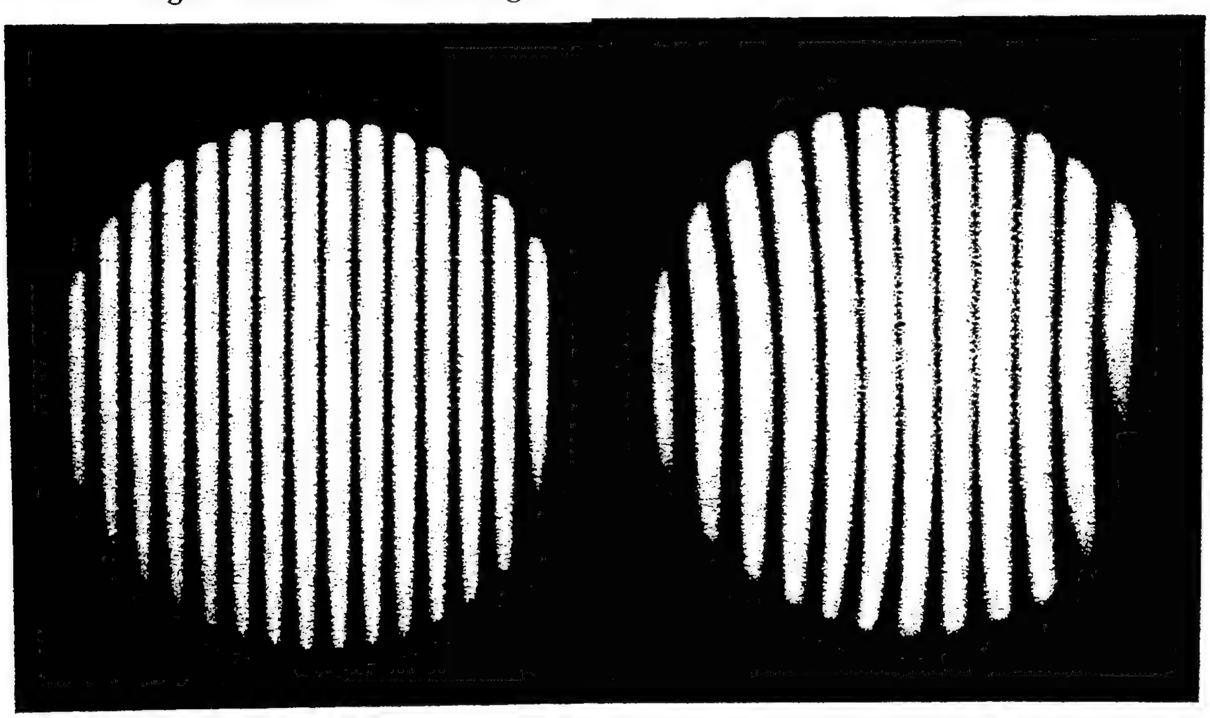


Figure 8: Illustration of Single Pass Ronchi Distortion Test Apparatus.



Reference (no Sample) WD1 Spectacle Lens

Figure 9: Example of Ronchi Distortion Test Patterns Recorded for WARDOVE Spectacle Lenses.

Haze

Definition and Significance. Haze is the term used to describe the scattering of light by a transparent material such as eyewear. Light can be scattered from the surface of the eyewear or from the eyewear material itself. Haze can cause reductions in contrast of visual targets and can be a particular problem when the eyewear is illuminated with bright sources of light. The light that is scattered by the eyewear from a bright light source (such as the sun) can cause what is termed veiling glare. Veiling glare can cause significant reduction in visual target contrast and can, in worse cases, mask the target entirely. Haze has been found to be more degrading to vision when the luminous transmittance of eyewear is reduced. Since LEP eyewear normally has reduced luminous transmittance, it is important to keep the haze to a minimum. The amount of allowable haze is specified for the eyewear in its original condition. Haze is also used to measure the effect of various abrasion tests. The haze of the eyewear measured before the abrasion test is compared to the haze after the test. MIL-V-43511C specifies that the haze be measured in accordance with ASTM-1003. This test method measures the light scattered at angles greater than 2.5 °. The ratio of the light scattered at angles greater than 2.5° to the total amount of light transmitted is defined as haze and is measured in percent. The allowable value for haze, specified in MIL-V-43511C, is 2%. The definition, measurement, and vision effects of haze are extremely important in the development of laser eye protection and are admittedly not fully understood. It was found during flight tests that some pilots complained that ALEP visors were hazy even when they met the 2% haze requirement. This finding may be a result of the fact that aircrews view not only through the LEP, but also through the aircraft canopy. The total haze that effects aircrew vision is a function of the combined haze of the eyewear and the canopy. The subjective impression of haze may have been due to the reduced luminous transmittance of the LEP, to the spectral transmittance characteristics, or to a combination of these properties. The recommended allowable haze value for LEP that is to be used in flight operations is 1% or less.

Haze Test Method and Instrument. The test method for measuring the haze of the WARDOVE samples is given in ASTM 1003-92. An apparatus that performs haze measurements in accordance with ASTM 1003-92 is shown schematically in Figure 10. The XL-211 Hazegard® and the newer Hazegard Plus Instrument, manufactured by BYK-Gardner, Inc., are both instruments that perform haze measurements in accordance with ASTM 1003-92. WARDOVE spectacle lens haze was measured at the center of each lens with both the XL-211 Hazegard (no serial number) and the Hazegard Plus (serial number 634712) instruments.

XL-211 Hazegard® Measurement Procedure. With no sample in place the XL-211 Hazegard® digital display is set to zero with the exit port open and to 100% with the exit port covered by the moveable reference. The sample is placed at the entrance port and two readings are taken: the diffuse transmission of the sample is read on the digital display with the exit port covered, and the raw haze value is read with the exit port open. The percent haze is computed by dividing the raw haze reading by the diffuse transmission. The diffuse transmittance measured by the XL-211 Hazegard® is the photopic luminous transmittance because of the spectral weighting of the detector that is used. When the XL-211 is adjusted according to procedures, a residual haze is present due to scattering within the instrument itself. This residual haze, or any method for compensating for it, is not discussed in the BKY Gardner operating manual. Residual haze is a small effect when the transmittance of the sample is high. The relative impact of the residual haze increases as the transmission decreases. An adjusted haze value can be

computed that compensates for the residual haze in the instrument and the transmittance of the sample.

Hazegard Plus Measurement Procedure. The Hazegard Plus instrument is a newer, more automated instrument and is sold by BKY Gardner as the replacement for the XL-211. The adjustment and operation of the Hazegard Plus is guided by a computer-controlled display. Although this instrument is more convenient to use, the insight as to how the measurements are being performed is lost. The Hazegard Plus reads transmission, haze and clarity. Clarity is not, as yet, an accepted standard performance parameter. Clarity is a measure of the light scattered into a small angular region (0.15 °) compared to the light that is transmitted directly. A perfectly clear sample would have a clarity of 100%. Clarity is measured with the sample at the exit port of the light source.

A set of calibrated, NIST traceable, haze standards with haze values ranging from .2 % to 35.8% is used to verify the performance of both hazemeters. The haze standards used to verify the calibration of the hazemeters prior to and after measurement of the WARDOVE samples were H-2643-96, calibration # FC 19805. The haze values measured with both of the instruments was typically within .02% of the calibrated values for haze values less than 4%.

Haze Results. The measured transmission, haze and clarity values for the WD1 and WD2 spectacle lenses are given in Tables 3 and 4. For the XL-211, measured and computed values for the transmission, raw haze, computed haze, and the haze adjusted for residual haze are given. For the Hazegard Plus, the readings for transmission, haze and clarity are given. The clarity measured for all WARDOVE spectacle lenses was greater than 99.5%. With the exception of one WD1 spectacle, all WARDOVE spectacle lenses had measured haze values less than 2%. The WD1 lenses had, in general, slightly higher haze than the WD2 lenses. The haze values measured with the two instruments differed by as much as 0.5%, which is more than what is expected for instrument error. The reasons for the variations in measured haze values between the two instruments are not known. The differences may have been caused by the specific spectral transmission characteristics of the samples and the two different instruments. The percent transmission measured with the Hazegard Plus was 4 to 5 % higher than the transmission measured with the XL-211. The transmission measured with the XL-211 was 4 or 5 % higher than the photopic luminous transmittance for illuminant C that was computed from the spectral transmittance data (discussed below). The variation of luminous transmittances with the different instruments is significant and not understood. It is expected that the differences in measured transmittance values for the WARDOVE samples result from the particular geometries of the different instruments, the lens spectral transmission and instrument spectral sensitivity, the reflective nature of the WARDOVE lenses, or a combination of these factors. Further investigation is needed to understand the variation in measured haze and photopic luminous transmittance values. Instrumental malfunction or lack of calibration was not the cause of the variations. The functioning and calibration of all instruments was checked and rechecked before, during, and after measurement of the WARDOVE samples.

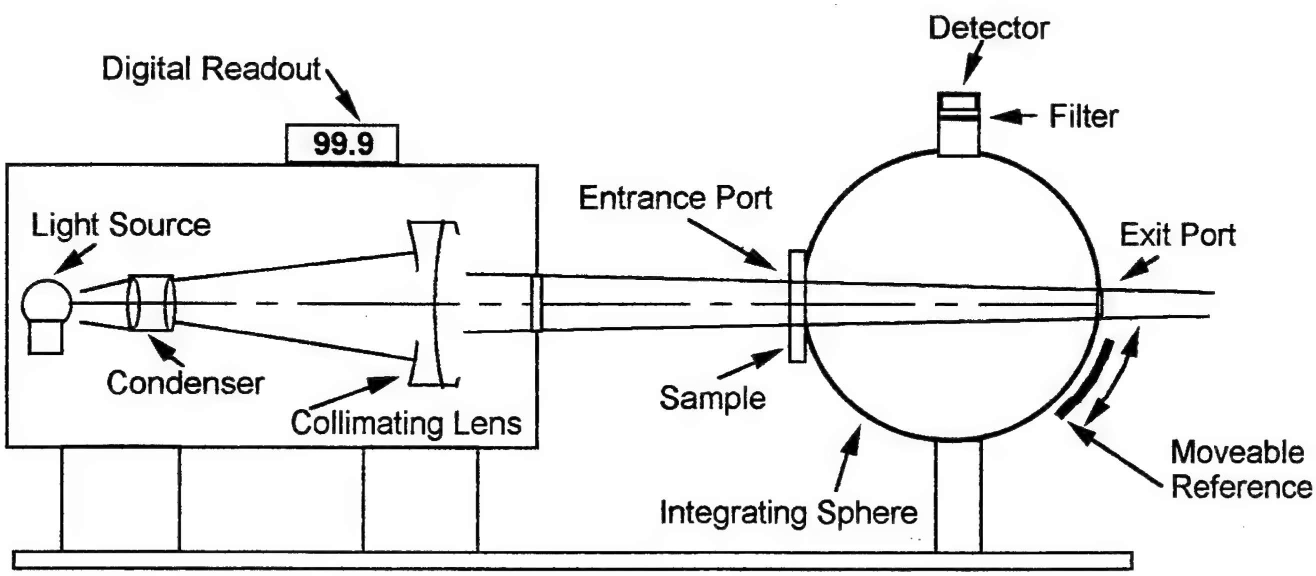


Figure 10. Schematic Illustration of Instrument for Measuring Haze in Accordance with ASTM 1003-92.

Transmittance

Spectral Transmittance

Definition and Significance. Spectral transmittance is one of the most important and complete measures of the performance of laser eye protection eyewear. Spectral transmittance is a wavelength-dependent quantity defined as the transmitted radiant energy at a specific wavelength divided by the incident radiant energy at that same wavelength. Transmittance is expressed as a decimal fraction or in percent. For most LEP the wavelength region of interest for transmittance is from 200 to 1200 nanometers (nm). The range between 200 nm and 380 nm is the ultraviolet (UV) region, between 380 nm and 780 nm is the visible region, and between 780 nm and 1200 nm is the near infrared (NIR) region of the spectrum. Laser eye protection must have low transmittance at the laser protection and UV wavelengths and high transmittance for visible, non-protection, wavelengths for effective viewing. Spectral transmittance is normally displayed in graphical form as a plot of transmittance (ordinate) versus wavelength (abscissa). Commercially available spectrophotometers automatically scan through the wavelengths of light and measure the transmittance of materials as a function of wavelength. Spectrophotometers can also provide spectral transmittance data in terms of optical density. Optical density is inversely and logarithmically related to transmittance as defined in the following equations:

$$OD_\lambda = \log_{10}(1/T_\lambda), \qquad (1)$$

or inversely,

$$T_\lambda = 1/10^{OD_\lambda}, \qquad (2)$$

where,	OD_λ	=	optical density, at wavelength λ,
	T_λ	=	transmittance, at wavelength λ,
and	$\log_{10}$	=	base 10 logarithm

The optical density provides an expanded scale for considering transmittance in portions of the wavelength spectrum with very low transmittance. Optical density (OD) is particularly useful for understanding the level of laser protection provided and is normally the way that laser protection requirements for LEP are specified. Since optical density is based on transmittance, it includes the attenuation of the incident light that results from both absorption and reflection. Most commercial spectrophotometers can perform reliable measurements of optical density only to a level of 4.0 OD. Although a commercial spectrophotometer may read and provide digital values of OD for much higher than 4.0, these values may be erroneous and great caution must be used in evaluating output data from a spectrophotometer.

Numerous vision protection and performance parameters are computed from the spectral transmittance data. Within the limits of the instrument, laser protection by LEP is determined from the spectral optical density measured at the laser protection wavelength(s). The protection provided in the UV portion of the spectrum is determined by integrating the transmittance in the 200 to 400 nm portion of the spectrum and calculating the average UV transmittance. The luminous transmittance for both photopic (day) and scotopic (night) vision is calculated from the spectral transmittance data as described below. The color performance of the LEP is characterized by calculating the CIE chromaticity coordinates using the CIE spectral tristimulus values and the spectral transmittance of the LEP.

The performance goal of the WARDOVE LEP is to block all nonvisible wavelengths (i.e., UV and NIR). This is commonly referred to as Out-of-Band Laser (OBL) protection. Ideal OBL protection will not reduce overall visibility and will not affect perceived color. An additional performance goal for the WD1 coating was to provide protection at the ruby laser wavelength. The ruby laser emits at 694.3 nm which is in the far red region near the edge of the visible range. The goal of the WD1 coating is to provide protection at the ruby wavelength but not significantly block shorter wavelengths. The effect on visible transmittance and the change in color should be small. The WD2 coating transmits a greater portion of the visible spectrum but does not provide any protection against the ruby laser. The comparison of the vision performance with the WD1 LEP (with ruby protection) and the WD2 LEP (without ruby protection) is one of the principal objectives of the WARDOVE program. The spectral transmittance measurements permit the assessment of the WARDOVE LEP in terms of meeting these performance goals. Blocking or attenuating any portion of the visible spectrum will cause a reduction of luminous transmittance (scene brightness) and may cause the perceived color of a scene to change. Reduced transmission can have an adverse effect on nighttime LEP use. A color shifting effect can have a dramatic impact on the compatibility of the LEP with aircraft cockpit lighting where much of the information is color-coded.

Spectral Transmittance Test Method and Instrument. A Cary 5G scanning spectrophotometer (instrument number EL 96013063) manufactured by Varian, Inc. was used to measure and record the spectral transmittance of the WARDOVE spectacle lenses over the wavelength region from 200 to 1200nm. The Cary 5 was set to transition from visible to near infrared (NIR) operation at 875nm. The mode of operation was Auto, which means that the instrument operates with a fixed slit width in the UV-vis and variable slit (fixed energy) mode in the NIR. The Spectral Bandwidth (SBW) in the visible and UV was set to 1nm. The scan rate was 30nm/sec and the response time was 0.5 seconds. Transmittance measurements were sampled in 1nm increments over the 200 to 1200nm region. The WARDOVE samples were

placed in the spectrophotometer chamber in an angle adjustable mount so that the transmittance at different angles of incidence could be measured. Retroreflection of the spectrophotometer beam was used to align the sample to be normal to the beam path. Complete spectral scans were performed for each of the spectacle lenses at 0, 30, and 50 degrees from the surface normal. The samples were rotated in the horizontal direction (about a vertical axis).

The CARY 5 is capable of measuring optical densities up to 4.0 at all wavelengths from 200 to 1200 nanometers. Beyond an optical density of 4.0, the accuracy of the measurement is reduced and is a function of the measurement wavelength. Even though the actual scan data produced optical density results beyond 4.0, all optical density scans were clipped at 4.0 to ensure the measurement accuracy was not overstated. Therefore, when an optical density scan in this report indicates 4.0 OD, the actual optical density is at least 4.0.

Spectral Transmittance Results. The complete spectral transmittance and optical density curves for each of the WARDOVE spectacle lenses are included as Appendix A. The curves are given for 0, 30 and 50 degrees from normal incidence. Calculated data such as photopic and scotopic luminous transmittance, CIE chromaticity coordinates, UV transmittance and optical densities at ten common laser wavelengths are given on each of the curves. The spectral transmittances measured on the WARDOVE lenses show that the curves are nearly ideal in terms of the transmittance performance goals. A portion of the blue end of the visible spectrum from 380 to 420nm is attenuated at a zero angle of incidence. The WD1 coatings attenuate the red portion of the spectrum from 650nm into the NIR. This red attenuation provides the ruby laser protection required of the WD1 LEP. The WD2 coatings have higher transmittance in the blue and red regions of the spectrum than the WD1 coatings and transmit well from 415 to 750nm. The spectral curves of both coatings shift toward the blue as the angle of incidence increases. This is an expected effect with dielectric thin film coatings due to the interference nature of the coating and the difference in optical paths at different angles of incidence. Some of the WD1 coated samples evidence a reduction in transmittance in the 590nm region for normal incidence. The wavelength at which this transmittance dip occurs shifts and the amount of reduction increases as the angle of incidence is increased. The transmittance curves for the WD2 coating evidences dips in transmittance at several locations as the angle of incidence increases. Some variations in the spectral transmittance curves is evident from lens to lens for both the WD1 and WD2 coatings. Figure 11 shows a typical variation in transmittance as a function of angle of incidence for the WD1 WARDOVE spectacles. Figure 12 shows the spectral optical density shift as a function of angle of incidence for the same WD1 sample. Figure 12 shows the OD equivalent of the transmittance curve shown in Figure 11. The OD plot indicates that for all wavelengths outside of the visible region, the transmission is reduced by at least four orders of magnitude (i.e., 4 OD). This means that the transmittance is 0.0001, or 0.01%, or less.

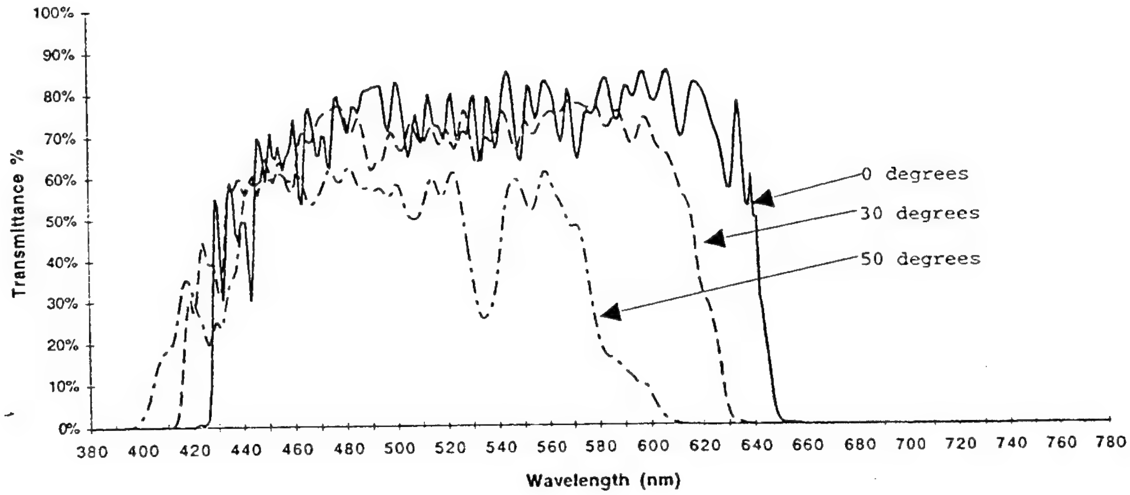


Figure 11: The Spectral Transmittance Plot of WD 1 Spectacle Lens Q--S1- at 0, 30 and 50 Degree Angles of Incidence.

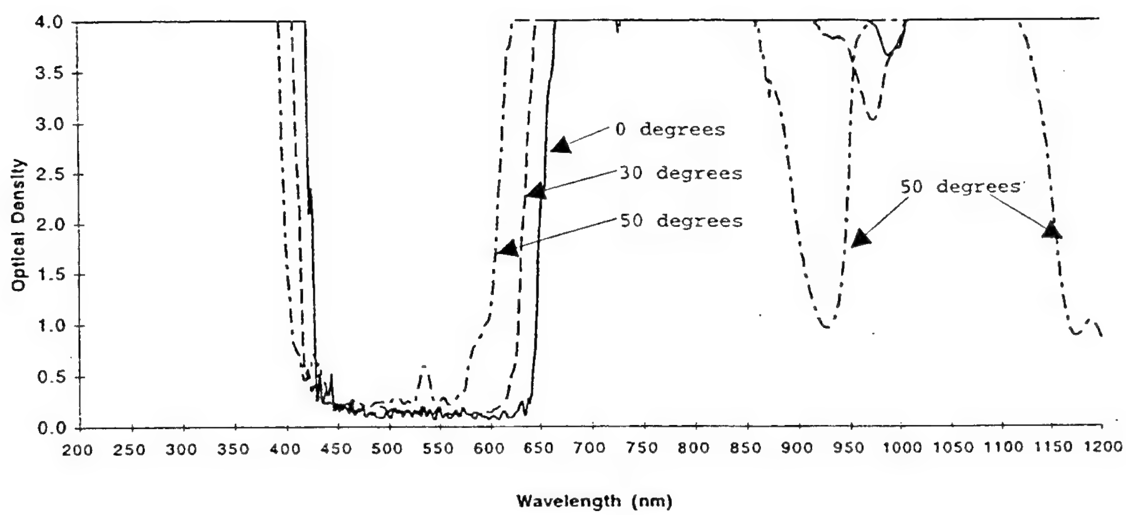


Figure 12: The Spectral Optical Density of WD1 Spectacle Lens Q--S1- at 0, 30 and 50 Degree Angles of Incidence.

Luminous Transmittance

Definition and Significance. The luminous transmittance is a measure of the amount of light that is transmitted by a material that is useable to the human eye. The luminous transmittance of a material depends on its spectral transmittance, the spectral content of the light source viewed through the material, and the spectral response of the eye. The spectral content of the light source is critical to the definition of the luminous transmittance. Typically, a standard illuminant defined by the Commission Internationale de l'Eclairage (CIE) is used to compute or measure the luminous transmittance. The sensitivity of the human eye varies with wavelength and state of adaptation. The response of the eye is given by the photopic (light adapted) and scotopic (dark-adapted) luminous efficiency functions for light and dark adapted vision. The efficiency functions are defined for a standard observer and provided in numerous texts. The photopic luminous transmittance (PLT), based on the standard Illuminant C, is a measure of the apparent brightness of natural scenes viewed through the material. The PLT represents the luminous transmittance for the light-adapted eye (i.e., a daytime viewing condition), and the scotopic luminous transmittance (SLT) represents the luminous transmittance for the dark-adapted eye (i.e., a nighttime viewing condition).

Luminous Transmittance Method. The luminous transmittance of a material can be measured directly using a standard light source and a detector with a spectral response that matches the human eye response. Luminous transmittance values are measured in this manner by the hazemeters discussed above. A direct measurement of luminous transmittance is an integrated value dependent on the spectral match between the light source used and the standard light source, and the match between the spectral response of the detector and the human eye response. For a spectrally selective filter, the luminous transmittance integrated by the detector may have errors due to slight spectral variations in light source spectral content or detector response. The luminous transmittance can also be computed from the spectral transmittance.

The average luminous transmittance (LT) of a material is given by the general relationship:

$$LT = (1/k)\int_{380}^{780} T(\lambda)S(\lambda)V(\lambda)\mathrm{d}\lambda\,, \tag{3}$$

where,

$$k = \int_{380}^{780} S(\lambda)V(\lambda)\mathrm{d}\lambda\,, \tag{4}$$

and,

$T(\lambda)$ = spectral transmittance of material at wavelength λ,
$S(\lambda)$ = spectral intensity of standard Illuminant C,
$V(\lambda)$ = spectral luminous efficiency as a function of wavelength (scotopic or photopic) based on the CIE (1931) standard observer.

The average photopic and scotopic luminous transmittance values are calculated using the photopic or scotopic values of $V(\lambda)$ respectively. Both computed and directly measured values for photopic luminous transmittance were obtained for all of the WARDOVE lenses. The scotopic luminous transmittance, with illuminant C, was computed for all samples.

Luminous Transmittance Results. The PLT and SLT values computed from the spectral data are given in Tables 5 through 10. The LT values were computed for 0, 30 and 50 degree angles of incidence for both the WD1 and the WD2 samples. The PLT values measured with the hazemeters are given in Tables 3 and 4. These values were discussed above. The photopic luminous transmittances measured with the hazemeters and the PLTs computed from the spectral transmittance data were significantly different. As much as 10% difference in PLT values for the same lens were noted depending on the instrument or method use to obtain the value. The PLT and SLT computed from spectral transmittance data are considered to be more reliable and repeatable than those measured directly because of the sharp cut-on and cut-off edges of the spectral transmittance and the narrow band fluctuations of the transmittances of the WARDOVE samples. The average value for PLT for WD2 lenses (83%) was computed to be approximately 7% greater than the PLT of the WD1 lenses. The average value for SLT for the WD2 lenses (77%) was approximately 4% greater than for the WD1 lenses. For both types of coatings, the PLT and SLT values decreased as the angle of incidence increased. At higher angles of incidence, the WD1 lenses had higher SLT s than PLTs. The WD1 lenses had very large variations of SLT and PLT from lens to lens. The PLT varied as much as 10% and the SLT varied as much as 8% from lens to lens with the WD1 coating.

Sample		Transmittance (%) (illum. C)		Cary 5, Abs. (OD)		Laser Dens. (OD)			Chroma. Coords.	
	Scotopic	Photopic	nom. UV	694nm	1064nm	694nm	1064nm	X	Y	Z
Q01S1										
R	75.2	78.2	0.0	>4	>4	4.97	6.07	0.3205	0.3601	0.3194
L	74.6	77.3	0.0	>4	>4	5.06	6.01	0.3186	0.3596	0.3218
Average	74.9	77.8	0.0			5.02	6.04			
Q02S1										
R	71.7	74.3	0.0	>4	>4	4.41	6.15	0.3245	0.3686	0.307
L	71.7	73.1	0.0	>4	>4	4.95	6.11	0.3203	0.3612	0.3185
Average	71.7	73.7	0.0			4.68	6.13			
Q03S1										
R	71.8	73.7	0.0	>4	>4	4.44	6.10	0.3196	0.3626	0.3177
L	71.0	73.9	0.0	>4	>4	5.46	5.93	0.3261	0.3689	0.305
Average	71.4	73.8	0.0			4.95	6.02			
Q04S1										
R	70.9	73.3	0.0	>4	>4	5.43	5.87	0.3167	0.3556	0.3277
L	69.9	71.8	0.0	>4	>4	5.40	6.12	0.3142	0.3515	0.3343
Average	70.4	72.6	0.0			5.42	6.00			
Q05S1										
R	70.7	72.8	0.0	>4	>4	4.54	5.97	0.3239	0.3643	0.3118
L	72.7	74.7	0.0	>4	>4	4.54	5.72	0.3223	0.3653	0.3215
Average	71.7	73.8	0.0			4.54	5.85			
Q06S1										
R	74.6	77.7	0.0	>4	3.90			0.3211	0.3768	0.302
L	70.9	73.2	0.0	>4	>4			0.317	0.3546	0.3284
Average	72.8	75.5	0.0							
Q07S1										
R	71.9	73.5	0.0	>4	>4			0.3141	0.3506	0.3353
L	72.5	74.6	0.0	>4	>4			0.3169	0.3522	0.3309
Average	72.2	74.1	0.0							
Q08S1										
R	77.9	81.4	0.0	>4	>4			0.3201	0.3641	0.3157
L	77.7	80.6	0.0	>4	>4			0.3171	0.3164	0.3215
Average	77.8	81.0	0.0							
Q09S1										
R	75.2	77.5	0.0	>4	>4			0.3181	0.3175	0.3105
L	74.6	77.5	0.0	>4	>4			0.3194	0.3157	0.3049
Average	74.9	77.5	0.0							
Q10S1										
R	71.1	73.0	0.0	>4	>4			0.322	0.361	0.317
L	70.8	72.6	0.0	>4	>4			0.3216	0.3593	0.3191
Average	71.0	72.8	0.0							
Max	77.90	81.40	0.00			5.46	6.15			
Min	69.90	71.80	0.00			4.41	5.72			
Average	72.87	75.24	0.00			4.92	6.01			

Table 5: Transmittance, Laser Protection and Color Coordinate Data for WD1 WARDOVE Spectacle Lenses at 0 Degrees Angle of Incidence

Sample		Transmittance (%) (illum. C)		Cary 5, Abs. (OD)		Laser Dens. (OD)			Chroma. Coords.	
	Scotopic	Photopic	nom. UV	694nm	1064nm	694nm	1064nm	X	Y	Z
Q01S1										
R	74.1	71.0	0.0	>4	>4	5.63	6.19	0.2916	0.3362	0.3722
L	72.8	69.1	0.0	>4	>4	5.51	6.25	0.2893	0.3353	0.3755
Average	73.5	70.1	0.0			5.57	6.22			
Q02S1										
R	66.1	61.2	0.0	>4	>4	5.07	6.15	0.2925	0.3516	0.3559
L	65.3	59.4	0.0	>4	>4	5.26	5.98	0.2873	0.3462	0.3665
Average	65.7	60.3	0.0			5.17	6.07			
Q03S1										
R	59.9	65.6	0.0	>4	>4	4.83	6.32	0.2890	0.3430	0.3670
L	64.8	61.1	0.0	>4	>4	5.65	6.11	0.2979	0.3495	0.3526
Average	62.4	63.4	0.0			5.24	6.22			
Q04S1										
R	68.0	66.1	0.0	>4	>4	5.65	6.03	0.2845	0.3465	0.3690
L	68.4	69.0	0.0	>4	>4	5.60	6.24	0.3034	0.3460	0.3505
Average	68.2	67.6	0.0			5.63	6.14			
Q05S1										
R	64.3	60.3	0.0	>4	>4	5.49	5.99	0.2983	0.3453	0.3564
L	67.1	61.9	0.0	>4	>4	5.25	5.93	0.2924	0.3488	0.3588
Average	65.7	61.1	0.0			5.37	5.96			
Q06S1										
R	69.3	64.7	0.0	>4	3.91			0.2972	0.3536	0.3492
L	68.2	66.0	0.0	>4	>4			0.2868	0.3416	0.3716
Average	68.8	65.4	0.0							
Q07S1										
R	69.3	67.3	0.0	>4	>4			0.2876	0.3387	0.3737
L	70.4	67.8	0.0	>4	>4			0.2843	0.3414	0.3743
Average	69.9	67.6	0.0							
Q08S1										
R	74.5	70.3	0.0	>4	>4			0.2845	0.3425	0.3730
L	72.8	68.8	0.0	>4	>4			0.2829	0.3449	0.3722
Average	73.7	69.6	0.0							
Q09S1										
R	69.3	65.2	0.0	>4	>4			0.2987	0.3538	0.3474
L	68.7	64.4	0.0	>4	>4			0.2972	0.3580	0.3448
Average	69.0	64.8	0.0							
Q10S1										
R	65.6	61.2	0.0	>4	>4			0.2935	0.3480	0.3585
L	64.8	59.9	0.0	>4	>4			0.2913	0.3446	0.3641
Average	65.2	60.6	0.0							
Max	74.50	71.00	0.00			5.65	6.32			
Min	59.90	59.40	0.00			4.83	5.93			
Average	68.19	65.02	0.00			5.39	6.12			

Table 6: Transmittance, Laser Protection and Color Coordinate Data for WD1 WARDOVE Spectacle Lenses at 30 Degrees Angle of Incidence

Sample	Transmittance (%) (illum. C)			Cary 5, Abs. (OD)		Laser Dens. (OD)			Chroma. Coords.	
	Scotopic	Photopic	nom. UV	694nm	1064nm	694nm	1064nm	X	Y	Z
Q01S1										
R	60.3	49.3	0.0	>4	>4	4.91	5.90	0.2455	0.3107	0.4438
L	57.1	47.5	0.0	>4	>4	4.83	5.79	0.2487	0.3129	0.4385
Average	58.7	48.4	0.0			4.87	5.85			
Q02S1										
R	53.7	43.3	0.0	>4	>4	5.07	5.92	0.2557	0.3156	0.4287
L	52.0	39.6	0.0	>4	>4	5.25	5.74	0.3299	0.3072	0.4529
Average	52.9	41.5	0.0			5.16	5.83			
Q03S1										
R	39.8	50.0	0.0	>4	>4	5.08	6.11	0.2540	0.3094	0.4367
L	51.3	40.3	0.0	>4	>4	5.31	6.24	0.2488	0.3156	0.4357
Average	45.6	45.2	0.0			5.20	6.18			
Q04S1										
R	52.2	36.8	0.0	>4	>4	5.27	5.93	0.2011	0.3030	0.4959
L	62.8	55.6	0.0	>4	>4	4.89	5.86	0.2561	0.3333	0.4107
Average	57.5	46.2	0.0			5.08	5.90			
Q05S1										
R	48.3	39.1	0.0	>4	>4	5.60	5.54	0.2578	0.3209	0.4213
L	54.2	43.0	0.0	>4	>4	5.30	5.84	0.2559	0.3094	0.4347
Average	51.3	41.1	0.0			5.45	5.69			
Q06S1										
R	52.9	44.3	0.0	>4	3.96			0.2784	0.3301	0.3915
L	50.2	38.5	0.0	>4	>4			0.2202	0.3105	0.4693
Average	51.6	41.4	0.0							
Q07S1										
R	53.3	40.8	0.0	>4	>4			0.2194	0.3104	0.4702
L	55.5	37.8	0.0	>4	>4			0.1978	0.2880	0.5143
Average	54.4	39.3	0.0							
Q08S1										
R	57.8	46.0	0.0	>4	>4			0.2404	0.3203	0.4393
L	54.3	38.0	0.0	>4	>4			0.2130	0.3045	0.4825
Average	56.1	42.0	0.0							
Q09S1										
R	52.5	40.0	0.0	>4	3.97			0.2505	0.3211	0.4285
L	51.1	37.4	0.0	>4	>4			0.2427	0.3192	0.4382
Average	51.8	38.7	0.0							
Q10S1										
R	49.0	36.5	0.0	>4	>4			0.3275	0.3087	0.4538
L	47.5	39.9	0.0	>4	>4			0.2656	0.3184	0.4159
Average	48.3	38.2	0.0							
Max	62.80	55.60	0.00			5.60	6.24			
Min	39.80	36.50	0.00			4.83	5.54			
Average	52.79	42.19	0.00			5.15	5.89			

Table 7: Transmittance, Laser Protection and Color Coordinate Data for WD1 WARDOVE Spectacle Lenses at 50 Degrees Angle of Incidence

Sample	Transmittance (%) (illum. C)			Cary 5, Abs. (OD)		Laser Dens. (OD)		Chroma.Coords.		
	Scotopic	**Photopic**	**nom. UV**	**694nm**	**1064nm**	**694nm**	**1064nm**	**X**	**Y**	**Z**
Q01S2										
R	76.0	82.3	0.0	0.05	>4		6.76	0.3304	0.3468	0.3228
L	76.1	82.3	0.0	0.06	>4		6.75	0.3302	0.3461	0.3237
Average	76.1	82.3	0.0				6.76			
Q02S2										
R	78.5	83.0	0.0	0.08	>4		5.49	0.3269	0.3475	0.3256
L	76.1	81.3	0.0	0.10	>4		6.21	0.3285	0.3449	0.3267
Average	77.3	82.2	0.0				5.85			
Q03S2										
R	76.7	83.1	0.0	0.06	>4		5.09	0.3310	0.3480	0.3210
L	76.5	82.9	0.0	0.06	>4		6.65	0.3313	0.3469	0.3219
Average	76.6	83.0	0.0				5.87			
Q04S2										
R	76.8	83.0	0.0	0.05	3.91		4.70	0.3298	0.3442	0.3260
L	78.9	84.6	0.0	0.05	>4		6.80	0.3308	0.3532	0.3160
Average	77.9	83.8	0.0				5.75			
Q05S2										
R	76.7	81.8	0.0	0.10	3.80		4.18	0.3292	0.3472	0.3236
L	77.9	82.6	0.0	0.14	>4		6.68	0.3262	0.3436	0.3303
Average	77.3	82.2	0.0				5.43			
Q06S2										
R	77.4	82.8	0.0	0.07	>4			0.3290	0.3463	0.3247
L	77.4	82.7	0.0	0.01	3.90			0.3281	0.3463	0.3256
Average	77.4	82.8	0.0							
Q07S2										
R	77.5	82.6	0.0	0.10	>4			0.3276	0.3458	0.3266
L	77.1	82.5	0.0	0.10	>4			0.3288	0.3473	0.3239
Average	77.3	82.6	0.0							
Q08S2										
R	76.7	82.1	0.0	0.07	>4			0.3302	0.3514	0.3184
L	76.6	82.1	0.0	0.06	>4			0.3300	0.3507	0.3193
Average	76.7	82.1	0.0							
Q09S2										
R	77.1	82.3	0.0	0.09	>4			0.3298	0.3484	0.3218
L	77.1	82.4	0.0	0.10	>4			0.3286	0.3469	0.3253
Average	77.1	82.4	0.0							
Q10S2										
R	77.4	82.8	0.0	0.10	>4			0.3296	0.3480	0.3224
L	77.4	82.8	0.0	0.11	3.95			0.3292	0.3474	0.3234
Average	77.4	82.8	0.0							
Max	78.90	84.60	0.00	0.14			6.80	0.3313	0.3532	0.3303
Min	76.00	81.30	0.00	0.01			4.18	0.3262	0.3436	0.3160
Average	77.10	82.60	0.00	0.08			5.93			

Table 8: Transmittance, Laser Protection and Color Coordinate Data for WD2 WARDOVE Spectacle Lenses at 0 Degrees Angle of Incidence

Sample		Transmittance (%) (illum. C)		Cary 5, Abs. (OD)		Laser Dens. (OD)			Chroma. Coords.	
	Scotopic	Photopic	nom. UV	694nm	1064nm	694nm	1064nm	X	Y	Z
Q01S2										
R	73.7	77.2	0.0	0.17	>4		6.90	0.3269	0.3452	0.3279
L	73.5	76.7	0.0	0.15	>4		7.00	0.3267	0.3445	0.3289
Average	73.6	77.0	0.0				6.95			
Q02S2										
R	72.8	74.5	0.0	0.42	>4		6.24	0.3222	0.3350	0.3428
L	73.2	75.8	0.0	0.38	>4		6.35	0.3229	0.3387	0.3385
Average	73.0	75.2	0.0				6.30			
Q03S2										
R	74.3	77.8	0.0	0.15	>4		5.15	0.3282	0.3448	0.3270
L	75.3	78.7	0.0	0.14	>4		6.73	0.3271	0.3440	0.3289
Average	74.8	78.3	0.0				5.94			
Q04S2										
R	75.5	78.7	0.0	0.12	3.95		5.00	0.3266	0.3430	0.3303
L	74.6	77.0	0.0	0.13	>4		7.07	0.3275	0.3418	0.3308
Average	75.1	77.9	0.0				6.04			
Q05S2										
R	73.6	75.8	0.0	0.29	3.80		4.23	0.3222	0.3383	0.3396
L	74.2	76.2	0.0	0.60	>4		6.36	0.3214	0.3359	0.3427
Average	73.9	76.0	0.0				5.30			
Q06S2										
R	75.5	78.2	0.0	0.30	>4			0.3228	0.3390	0.3383
L	75.1	77.8	0.0	0.40	>4			0.3229	0.3388	0.3383
Average	75.3	78.0	0.0					0.3229	0.3389	0.3383
Q07S2										
R	74.7	76.5	0.0	0.39	>4			0.3208	0.3360	0.3432
L	75.1	77.4	0.0	0.28	>4			0.3225	0.3394	0.3381
Average	74.9	77.0	0.0							
Q08S2										
R	70.4	73.0	0.0	0.16	>4			0.3283	0.3487	0.3280
L	71.2	73.4	0.0	0.15	>4			0.3271	0.3430	0.3299
Average	70.8	73.2	0.0							
Q09S2										
R	74.3	76.6	0.0	0.32	>4			0.3225	0.3388	0.3388
L	74.5	76.8	0.0	0.42	>4			0.3229	0.3387	0.3384
Average	74.4	76.7	0.0							
Q10S2										
R	75.0	77.4	0.0	0.22	>4			0.3233	0.3372	0.3396
L	74.6	77.2	0.0	0.30	3.97			0.3235	0.3388	0.3377
Average	74.8	77.3	0.0							
Max	75.50	78.70	0.00	0.60			7.07	0.3283	0.3487	0.3432
Min	70.40	73.00	0.00	0.12			4.23	0.3208	0.3350	0.3270
Average	74.06	76.64	0.00	0.27			6.10			

Table 9: Transmittance, Laser Protection and Color Coordinate Data for WD2 WARDOVE Spectacle Lenses at 30 Degrees Angle of Incidence

Sample	Transmittance (%) (illum. C)			Cary 5, Abs. (OD)		Laser Dens. (OD)		Chroma. Coords.		
	Scotopic	Photopic	nom. UV	694nm	1064nm	694nm	1064nm	X	Y	Z
Q01S2										
R	55.4	59.7	0.0	0.82	>4		6.11	0.3334	0.3262	0.3403
L	55.8	60.3	0.0	1.07	>4		5.98	0.3339	0.3317	0.3344
Average	55.6	60.0	0.0				6.05			
Q02S2										
R	51.4	54.2	0.0	3.22	>4		5.74	0.3263	0.3284	0.3453
L	54.6	57.0	0.0	2.99	>4		6.36	0.3268	0.3247	0.3485
Average	53.0	55.6	0.0				6.05			
Q03S2										
R	55.8	61.8	0.0	0.77	3.98		4.95	0.3411	0.3359	0.3230
L	60.3	63.7	0.0	0.87	>4		5.97	0.3307	0.3308	0.3385
Average	58.1	62.8	0.0				5.46			
Q04S2										
R	57.8	63.4	0.0	1.14	3.97		5.26	0.3357	0.3317	0.3326
L	56.0	62.2	0.0	1.56	>4		6.23	0.3382	0.3358	0.3261
Average	56.9	62.8	0.0				5.75			
Q05S2										
R	52.6	55.2	0.0	2.87	3.88		4.80	0.3251	0.3283	0.3466
L	52.2	56.0	0.0	3.74	>4		5.23	0.3247	0.3292	0.3462
Average	52.4	55.6	0.0				5.02			
Q06S2										
R	55.3	57.9	0.0	3.19	>4			0.3229	0.3297	0.3473
L	57.3	60.7	0.0	2.82	>4			0.3286	0.3302	0.3412
Average	56.3	59.3	0.0							
Q07S2										
R	52.4	55.1	0.0	3.59	>4			0.3238	0.3288	0.3474
L	56.3	59.1	0.0	2.90	>4			0.3237	0.3293	0.3470
Average	54.4	57.1	0.0							
Q08S2										
R	47.5	52.3	0.0	1.23	>4			0.3369	0.3313	0.3318
L	47.6	53.8	0.0	1.38	>4			0.3428	0.3396	0.3176
Average	47.6	53.1	0.0							
Q09S2										
R	55.5	58.0	0.0	3.03	>4			0.3229	0.3270	0.3502
L	53.9	57.5	0.0	3.16	>4			0.3295	0.3283	0.3423
Average	54.7	57.8	0.0							
Q10S2										
R	57.1	59.1	0.0	3.14	3.99			0.3214	0.3255	0.3531
L	56.0	58.3	0.0	2.75	3.97			0.3218	0.3298	0.3484
Average	56.6	58.7	0.0							
Max	60.30	63.70	0.00	3.74			6.36	0.3428	0.3396	0.3531
Min	47.50	52.30	0.00	0.77			4.80	0.3214	0.3247	0.3176
Average	54.54	58.27	0.00	2.31			5.66			

Table 10: Transmittance, Laser Protection and Color Coordinate Data for WD2 WARDOVE Spectacle Lenses at 50 Degrees Angle of Incidence

CIE Chromaticity Coordinates

Definition and Significance. Since laser eye protection must block certain wavelengths of light and transmit others, there is concern regarding the color-shifting properties of the material. The impact of LEP on color vision is analyzed in terms of parameters defined by the Commission Internationale de l'Eclairage(CIE). The x and y coordinates on the CIE chromaticity diagram of a particular light source viewed through the LEP provides a measure of the color shift that can be expected. The CIE chromaticity diagram is discussed in numerous texts (see Electro-Optics Handbook). The CIE chromaticity coordinate values represent the x and y coordinates of a three-dimensional color mapping. A transformation is created that maps all colors onto a three-dimensional surface created by the equation:

$$x + y + z = 1. \tag{5}$$

Since three-dimensional surfaces are hard to plot and since the z coordinate can always be calculated from equation 5, only the x and y coordinates are used. The three-dimensional surface is then projected onto the two-dimensions of the calculated x and y coordinates. Each x,y point on the chromaticity diagram represents a color (hue and saturation). The boundary of the chromaticity diagram is the spectrum locus and represents the coordinates of single spectral wavelength (saturated) colors. The x and y coordinate values of .35 and .35 approximately represent a neutral filter for daylight conditions.

CIE Chromaticity Methods. The values of the x and y CIE chromaticity coordinates are obtained using:

$$x = \frac{X}{X+Y+Z}, \tag{6}$$

and,

$$y = \frac{Y}{X+Y+Z}. \tag{7}$$

X, Y, and Z are referred to as the tristimulus values and are calculated as,

$$X = \int_{380}^{780} T(\lambda)S(\lambda)\bar{x}(\lambda)\mathrm{d}(\lambda), \tag{8}$$

$$Y = \int_{380}^{780} T(\lambda)S(\lambda)\bar{y}(\lambda)\mathrm{d}(\lambda), \tag{9}$$

and,

$$Z = \int_{380}^{780} T(\lambda)S(\lambda)\bar{z}(\lambda)\mathrm{d}(\lambda), \tag{10}$$

where,

$T(\lambda)$ = Spectral transmittance of the material at wavelength λ,

$S(\lambda)$ = Spectral intensity of standard Illuminant C,

and, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = CIE (1931) standard observer (2°) spectral tristimulus values of the equal energy spectrum.

The chromaticity coordinates for the WARDOVE lenses were computed using the above methods and $T(\lambda)$ of the lenses from the spectral transmittance data.

CIE Chromaticity Results. Tables 5 through 10 give the x, y, and z chromaticity coordinates for all of the WD1 and WD2 filters at angles of incidence of 0, 30, and 50 degrees. The x values for both coatings are in the .32 to .33 region and the y values are in the .34 to .36 region. These chromaticity coordinates indicate that the WARDOVE lenses are nearly spectrally neutral. The chromaticity coordinates shift toward the blue as the angle of incidence increases but the shift is very slight for angles less than 50 degrees.

Mean Ultraviolet Transmittance

Definition and Significance. Aircrew eyewear is required to provide protection against the ultraviolet portion of the spectrum. Since different portions of the UV spectrum have different biological effects, the entire UV spectrum should be strongly attenuated by aircrew eyewear. Ultraviolet light can cause irritation of the cornea (sun burn), and long term exposures can result in cataracts (clouding of the lens). MIL-V-43511C requires that the integrated UV transmittance between 250 and 320nm be less than 1%. UV light can be effectively attenuated by absorption in the polycarbonate material with little, if any, penalty in visible transmittance.

UV Transmittance Method. The mean ultraviolet transmittance of the WARDOVE lenses was computed from the spectral transmittance data. The mean UV transmittance was computed as the average of the transmittance values at wavelengths from 250 to 400nm.

UV Transmittance Results. The values for UV transmittance of the WARDOVE lenses at three different angles of incidence are given in Tables 5 through 10. The mean UV transmittance of all WARDOVE lenses is less than .1 %. Excellent UV protection is afforded by the WARDOVE lenses.

Laser Protection

Laser Protection

Definition and Significance. The transmittance of a material at a specific laser wavelength is the measure of the amount of protection provided for that specific laser. The optical density at the specific laser wavelengths is normally used to specify or define the level of attenuation provided by LEP. The eye focuses and greatly concentrates laser light on the retina. A very small amount of laser light incident on the cornea can be focused to cause damage to the retina. The attenuation levels that must be provided by LEP are thus typically very high. An OD of 4.0 or greater is often required. Attenuation of the laser light by LEP eyewear must be sufficient to reduce the light level at the cornea to a safe level. The laser light can be attenuated by absorption in the LEP material or by reflection from a coated surface. LEP must attenuate the laser light for all potential angles of incidence. The transmittance of reflective LEP is sensitive to angle of incidence and the polarization of light. The spectral transmittance varies more with to angle of incidence for reflective LEP than for absorptive LEP. The measured optical density of LEP can change with the level of the incident laser light due to dynamic bleaching or other non-linear effects. Bleaching is primarily a problem with absorptive LEP, but the optical density of all LEP eyewear should be measured at the level of laser light that is expected, if possible. The use of a laser source to measure the transmittance allows the measurement of higher OD values, the control of the light polarization, and the use of high levels of incident light. The 1064nm

wavelength of NdYAG (Neodymium-Yittrium Aluminum Garnet) lasers used as target designators and range finders is the most commonly used laser wavelength in military applications. Protection from other laser wavelengths in the far red and near infrared portion of the spectrum is secondary, but often required. The WARDOVE WD1 spectacles are designed to protect against the 1064nm NdYAG laser and the 694.3nm Ruby laser. The WARDOVE WD2 spectacles are designed to protect against the 1064nm NdYAG laser only.

Laser Protection Test Methods and Instruments. The laser optical density of the WARDOVE spectacle lenses was measured using the Cary 5 spectrophotometer and a laser transmittance measurement system. The Cary 5 spectrophotometer was discussed above and is limited to measurement of optical densities less than 4.0. The laser measurement system used for the laser transmittance measurements of the WARDOVE samples is illustrated in Figure 13. A system such as this was used to measure the laser optical density at 1064nm and 694.3nm for the WD1 spectacles and at 1064nm for the WD2 spectacles.

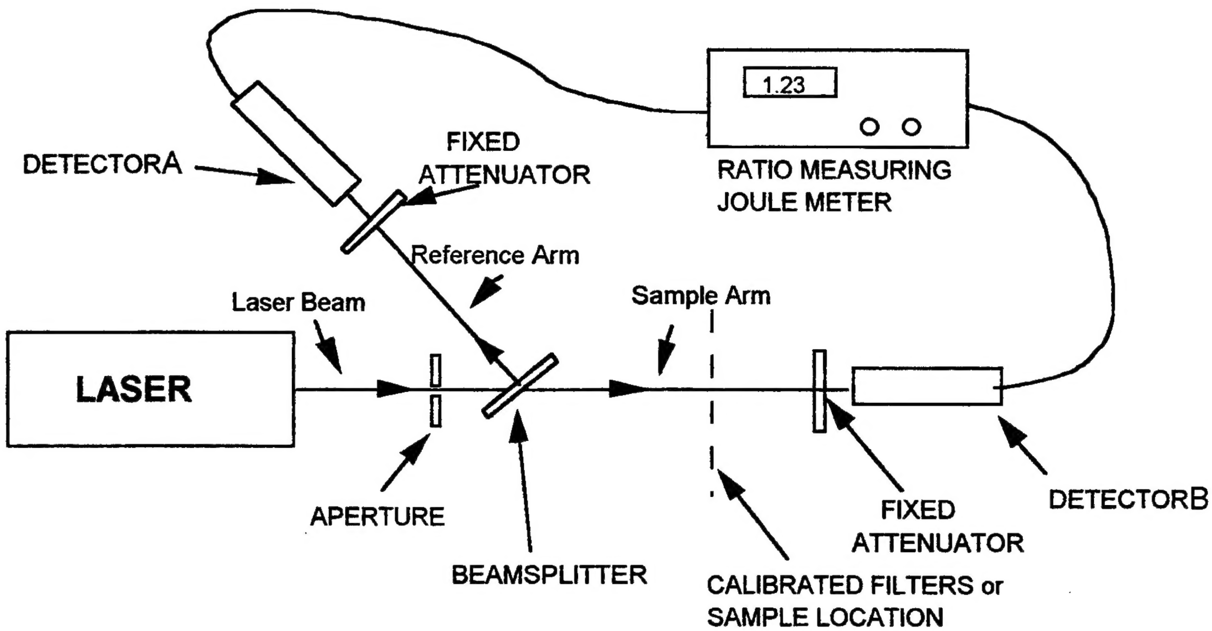


Figure 13: Illustration of Laser Optical Density Measurement Apparatus.

The specific instrumentation used to measure the WARDOVE samples was at the Walter Reed Army Institute of Research at Brooks AFB, TX. The laser used to measure the transmittance at 1064nm was a Quantel (Continum) NdYAG laser, Model YG-580-10, S/N 279, operating at 1064nm, 5 pps, 20ns pulses and providing 1.3mJ/pulse at the sample. The laser used to measure the transmittance at 694.3nm was a Molectron Dye laser, Model DL-16, with Exiton dye No. LDS-698, operating at 694nm, 20pps, and providing 86 microjoules per pulse. The dye laser was pumped by a Molectron Model MY 33-10, S/N 172, doubled NdYAG laser. The

wavelength of the dye laser was set to 694nm by tuning the rear grating reflector and monitoring the wavelength with a Burle Wavemeter Model 4000, S/N J7202304. A 4mm-diameter aperture placed between the laser and the beam splitter to define the area of the measurement. The NdYAG laser was adjusted to provide 1.3mJ/pulse through the aperture and beam splitter in order to provide $10mJ/cm^2$ at the sample. The laser beams were both linear polarized in the vertical direction. A glass wedged beam splitter was used to divide the laser beam into the sample and reference arms of the apparatus. The detectors and the ratio meter used were manufactured by Laser Precision. A RJ 735 pyroelectric detector was used in the sample arm (Detector B) when the laser power incident on the sample was adjusted. During calibration and measurements, Detector A, in the reference arm, was a RJ 735 pyroelectric detector and Detector B, in the sample arm, was a RJ 765 silicon detector. The meter was a RJ 7620 Ratio Meter, S/N 8808-01-12. The ratio meter provided displays of the individual outputs of the two detectors and a display of the ratio of the outputs of Detectors A and B. The meter was set to average 100 pulses before providing a reading. Fixed attenuating filters were used in front of the detectors to keep the levels of incident laser energy within the operating range of the detectors.

In order not to damage the detectors and to minimize the dynamic measurement range required of Detector B, the following method was used. Known neutral density filters, calibrated at the specific laser wavelengths, were placed in the sample arm. The total attenuation of the filters at the laser wavelength was chosen to provide attenuation near to the amount that was expected for the WARDOVE lenses. The laser was operated and measurements were made with Detectors A and B, including the ratio of B to A. The detector signal ratio with the neutral density filters was recorded from the meter as $(B/A)_{nd}$. The calibrated transmittance of the neutral density filters at the specific laser wavelength was recorded as T_{nd}. This operation was performed to calibrate the ratio of the beam in the sample arm to the beam in the reference arm, i.e. the beam splitter ratio. The neutral density filters were removed from the sample arm and WARDOVE samples were placed in the sample arm. The laser was operated and detector measurements were repeated with the WARDOVE samples. The ratio of the signal from Detector B to Detector A with the WARDOVE lens in place was recorded as $(B/A)_{sample}$. It can be shown that the transmittance of the sample is given by the following equation:

$$T_{sample} = \frac{\left(\frac{B}{A}\right)_{sample}}{\left(\frac{B}{A}\right)_{nd}} \times T_{nd} \tag{5}$$

The optical density of the sample can be calculated using equation (1) above. For the laser transmittance measurements, the WARDOVE lenses were held in a mechanical mount that permitted lenses to be rotated known amounts in the vertical direction (about a horizontal axis). The laser transmittance was measured for each of the WARDOVE lenses at 0, 30, and 50 degrees angles of incidence. The polarization of the laser light was in the "p" plane (parallel to the plane of incidence). This is the worst case condition in terms of laser light that might be transmitted through the filter.

Laser Protection Results. The measured values of optical density at the laser wavelength are given in Tables 5 through 10 for the WD1 and WD2 lenses at the three angles of incidence. The optical densities at the laser wavelengths measured on the Cary 5 are greater than 4 with the exception of two lenses. The optical densities measured using the laser measuring system show that the WD1 lenses have laser optical densities ranging from 4.4 to 5.7 at the 694nm laser line, and ranging from 5.5 to 6.3 for the 1064nm laser line at angles of incidence up to 50 degrees. The WD2 lenses have measured optical densities ranging from 4.2 to 7.1 for the 1064nm laser line at angles of incidence up to 50 degrees. These results show that the WARDOVE LEP spectacles provide a high level of laser protection out to 50 degrees from normal incidence.

REFERENCES

American National Standards Institute, ANSI Z 58.7.1-1951: Measuring and Specifying Color.

American National Standards Institute, ANSI Z 80.1-1995: Prescription Ophthalmic Lenses-Recommendations.

American National Standards Institute, ANSI Z 80.5-1979: Requirements for Dress Ophthalmic Frames.

American National Standards Institute, ANSI Z 80.3-1977: Requirements for Nonprescription Sunglasses and Fashion Eyewear.

American National Standards Institute, ANSI Z 87.1-1989: Practice for Occupational and Educational Eye and Face Protection.

American Society for Testing of Materials, ASTM 1003-92: Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics.

American Society for Testing of Materials, ASTM D3359-83: Standard Methods for Measuring Adhesion by Tape Test.

Electro-optics Handbook, TP-135, Burle Industries,Inc., Lancaster, PA.

MIL-L-38169, Military Specification: Lenses, Goggle and Visor, Helmet Optical Characteristics.

MIL-V-43511C, Military Specification: Visors, Flyer's Helmet, Polycarbonate.

MIL-V-85374, Military Specification: Visors, Shatter Resistant.

MIL-V-XXXXX, Military Specification: Visors, Aviator, Laser Protective Polycarbonate (currently in draft form).

Maier, D.A. and LaPage, C.S.: Failure Mechanisms in Aircrew Helmet Visors, AL/OE- TR-1996-0117, September 1996.

Maier, D.A.: Scratch Resistance Testing of Pilot Helmet Visors Using a New Scratch Resistance Tester, AL/OE- TR-1996-0140, December 1996.